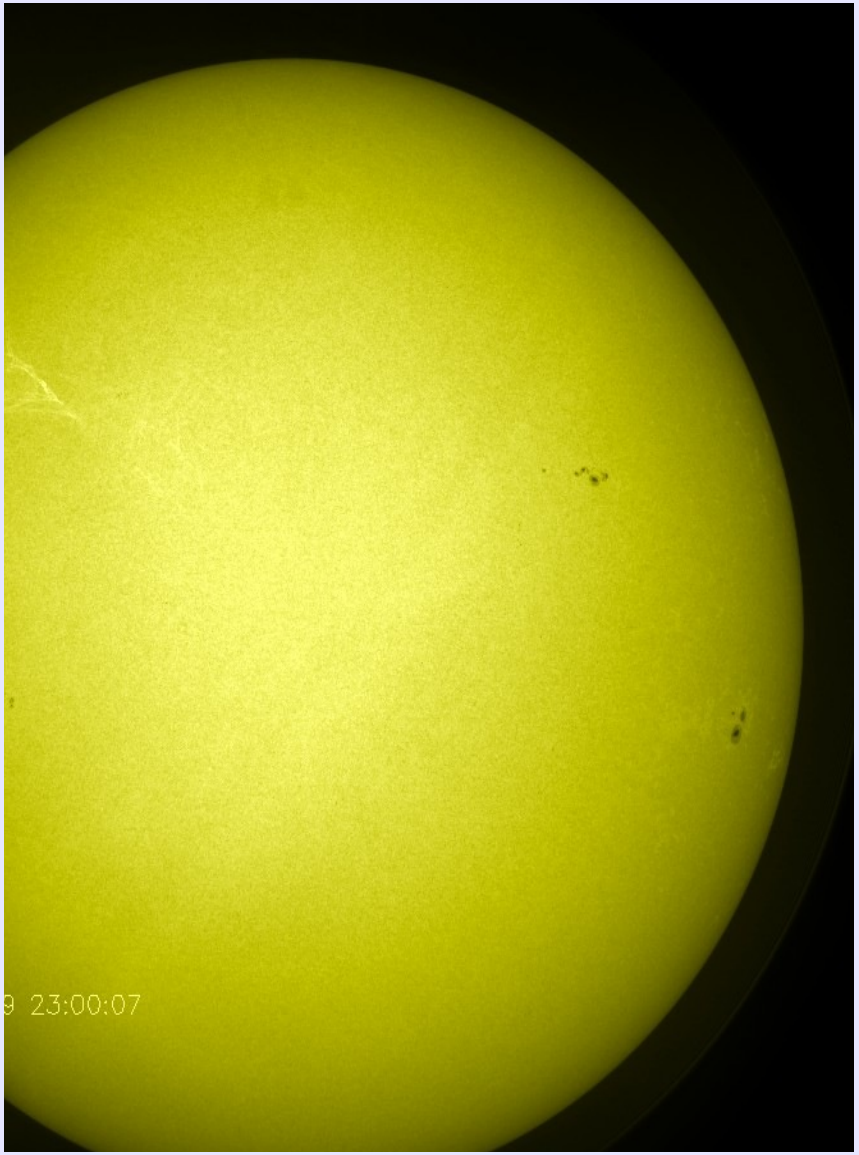
# Forecasting Solar Flares: Status and Recent Developments

**KD Leka, Graham Barnes, Doug Braun, Eric Wagner**
*NorthWest Research Associates*

Funding for this work is acknowledged from NOAA/SBIR contract WC-133R-13-CN-0079.
Leka, Barnes and Wagner acknowledge additional support from NASA NNH09CE72C, NNH12CG10C, and Braun through NSF grant AGS-1127327.

# Q: Who needs flare forecasts?



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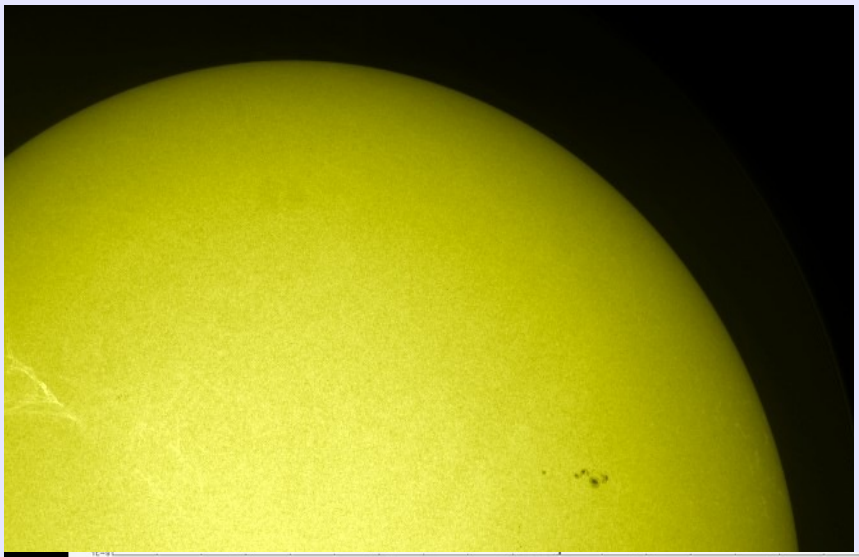
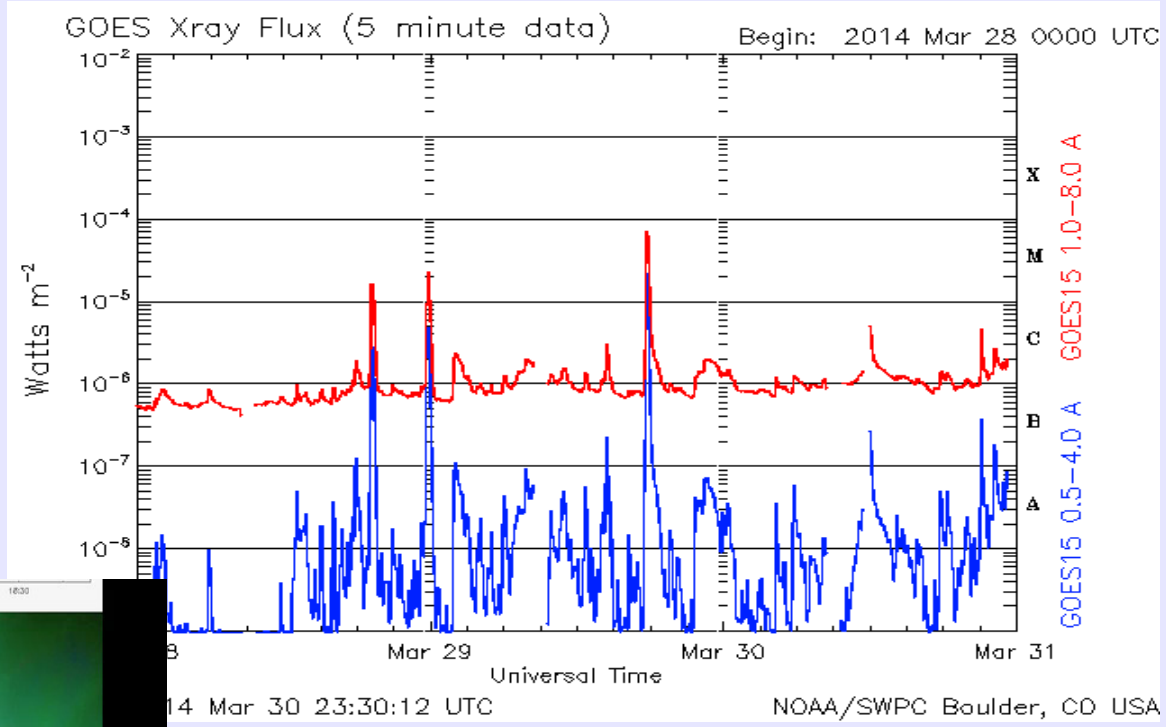
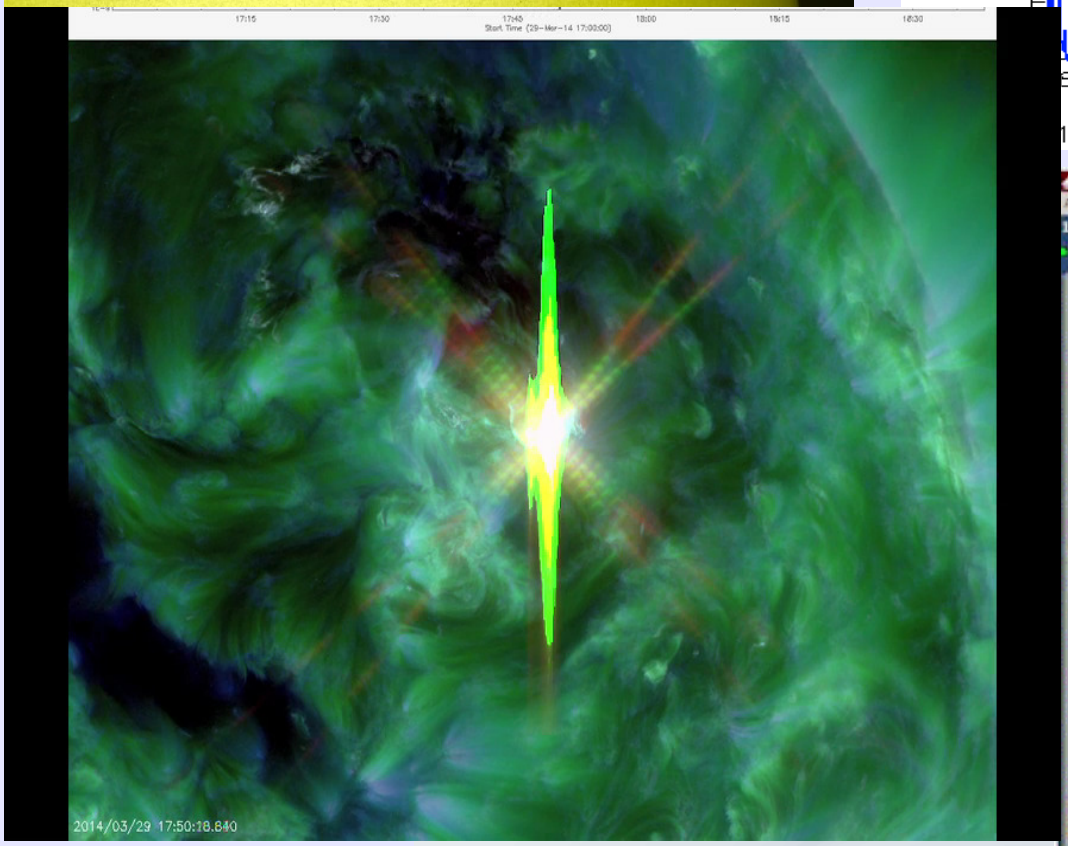
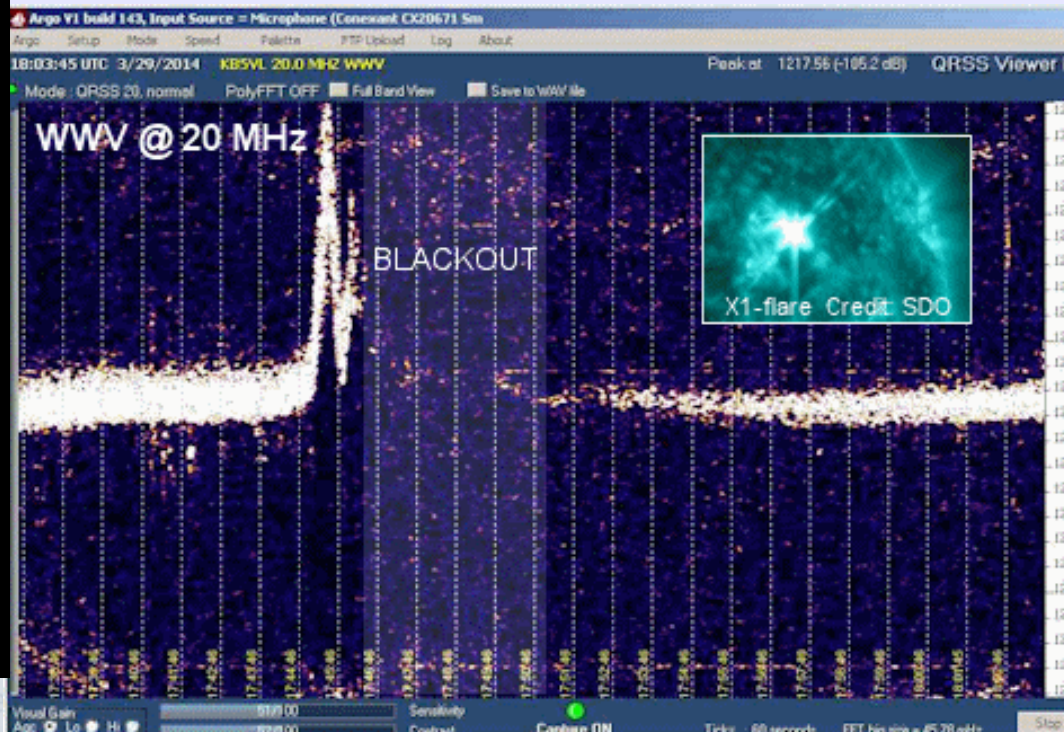





*Images courtesy NOAA/GOES, SDO, spaceweather.com*

## Q: Who needs flare forecasts?
## A: Who's asking? and Why?

- ***Time-of-flight = c***
  - **Space Assets (including humans)**
  - **High-Altitude radiation exposure**
- ***Ionospheric/Stratospheric effects: few minutes.***
  - **Communications/Time/Location**
- ***Geomagnetic impacts***
  - **Association with CMEs/SEPs**
- ***Science/Physics/Mathematics/Computer Science***
  - **Basic physics (forecasting is the best test of understanding)**
  - **Statistical methods of forecasting rare events.**

## Why this is hard, I: *we do not understand the physics.*

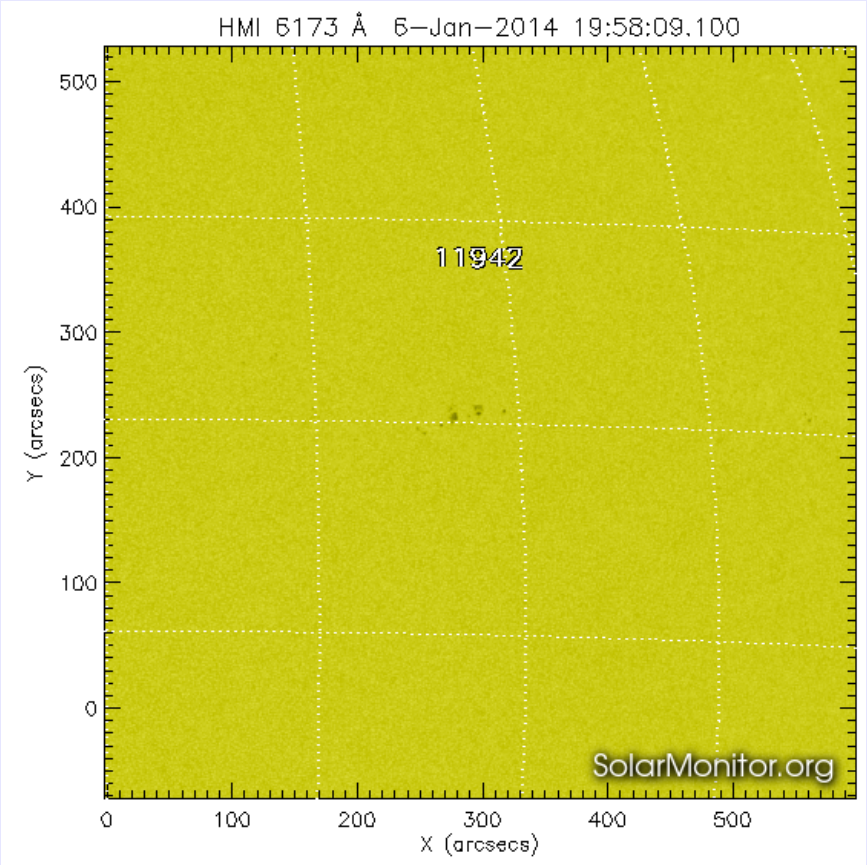
To flare, a solar active region must be **“Big, Bad, and Angry”**

# Why this is hard, I: *we do not understand the physics.*

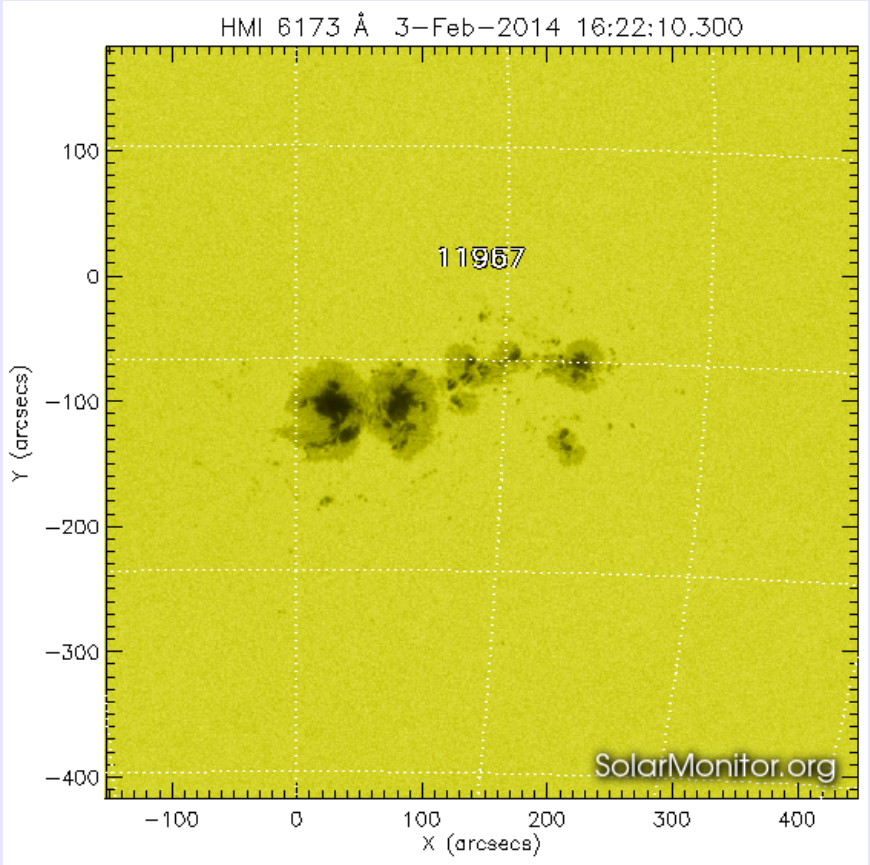
**"Causes of Flares": *Big***

- Larg(er) active regions are more flare productive.
- More magnetic energy $B^2/8\pi$

**no**




**yes**

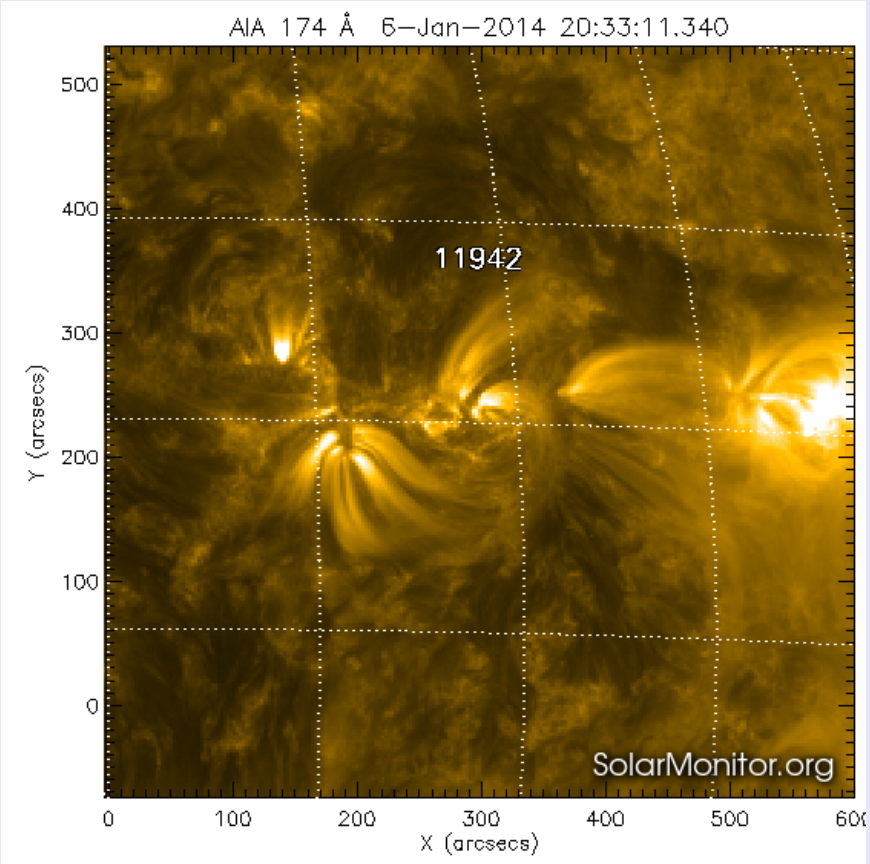


# Why this is hard, I: *we do not understand the physics.*

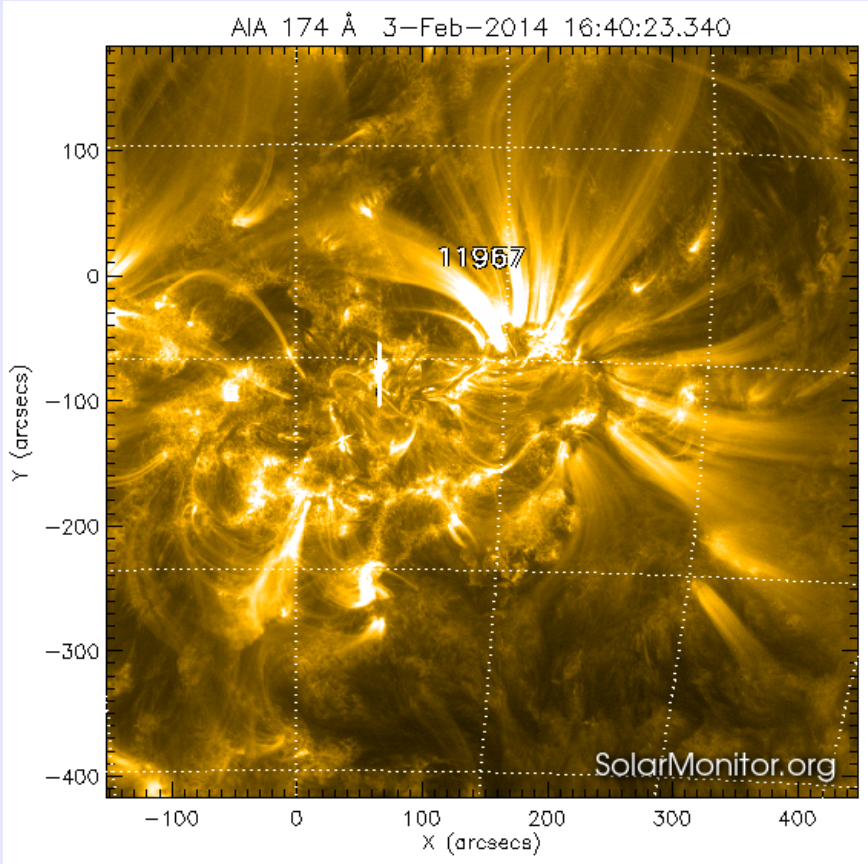
**"Causes of Flares": *Bad***

- **Non-potential, complex, "tangled" active-region magnetic fields.**
- **Indicates significant "free magnetic energy" is available.**
- **Indicates more "options" for the corona to begin reconnection.**

**no**



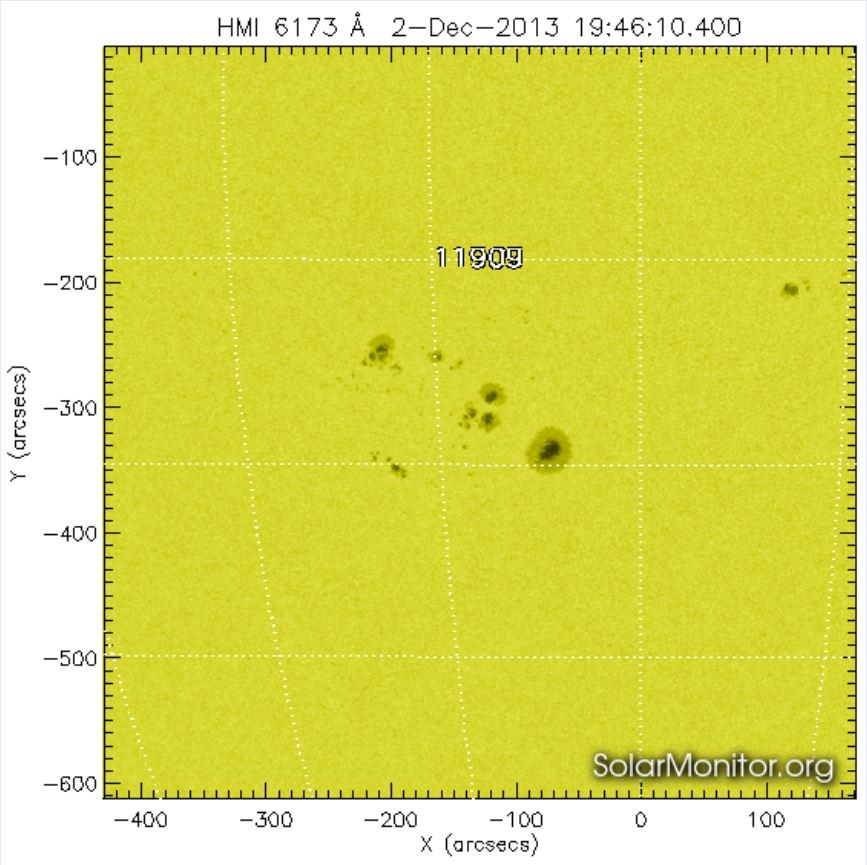

**yes**

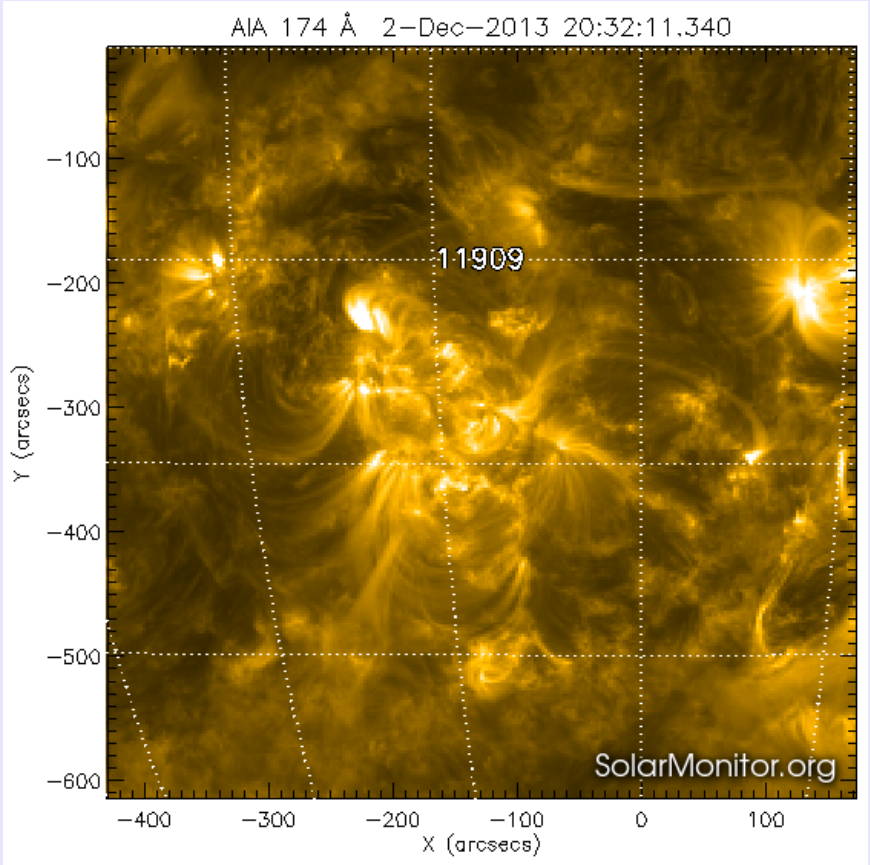


# Why this is hard, I: *we do not understand the physics.*

***Flaring and Flare-Quiet regions can be very similar, at any given moment.***

**maybe...**

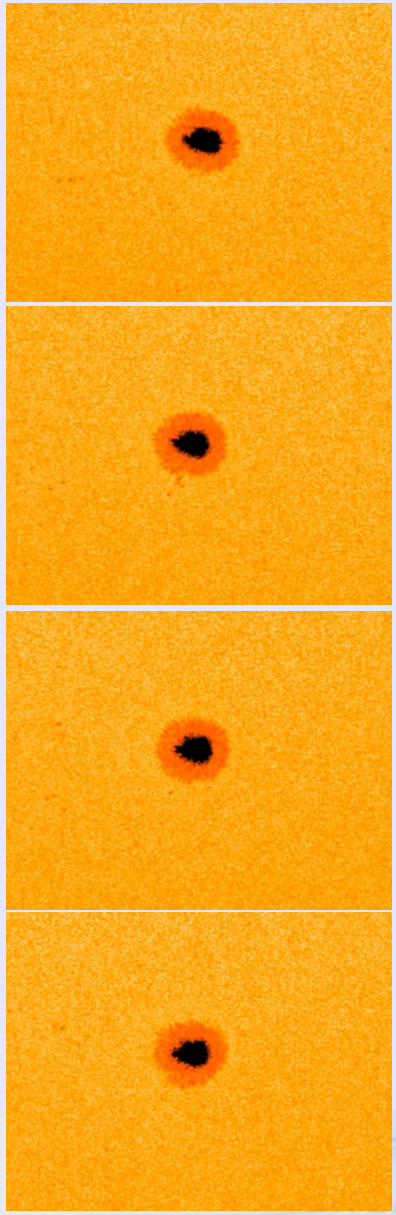


# Why this is hard, I: *we do not understand the physics.*

**"Causes of Flares": *Angry***

- Rapidly evolving.
- New sunspots emerging close to old ones.

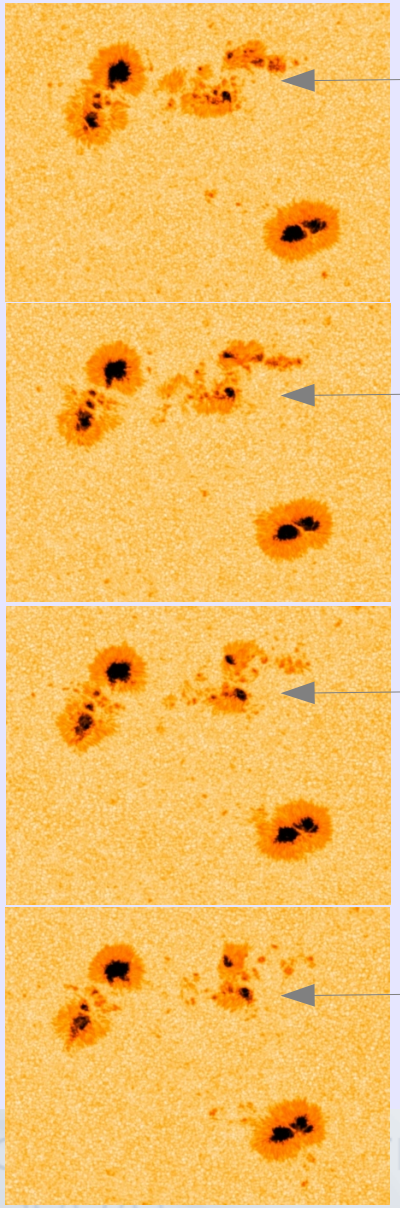


00:00 UT

01:00 UT

02:00 UT

03:00 UT



*(the Hint arrow)*

***Low** flare likelihood*

***High** flare likelihood*

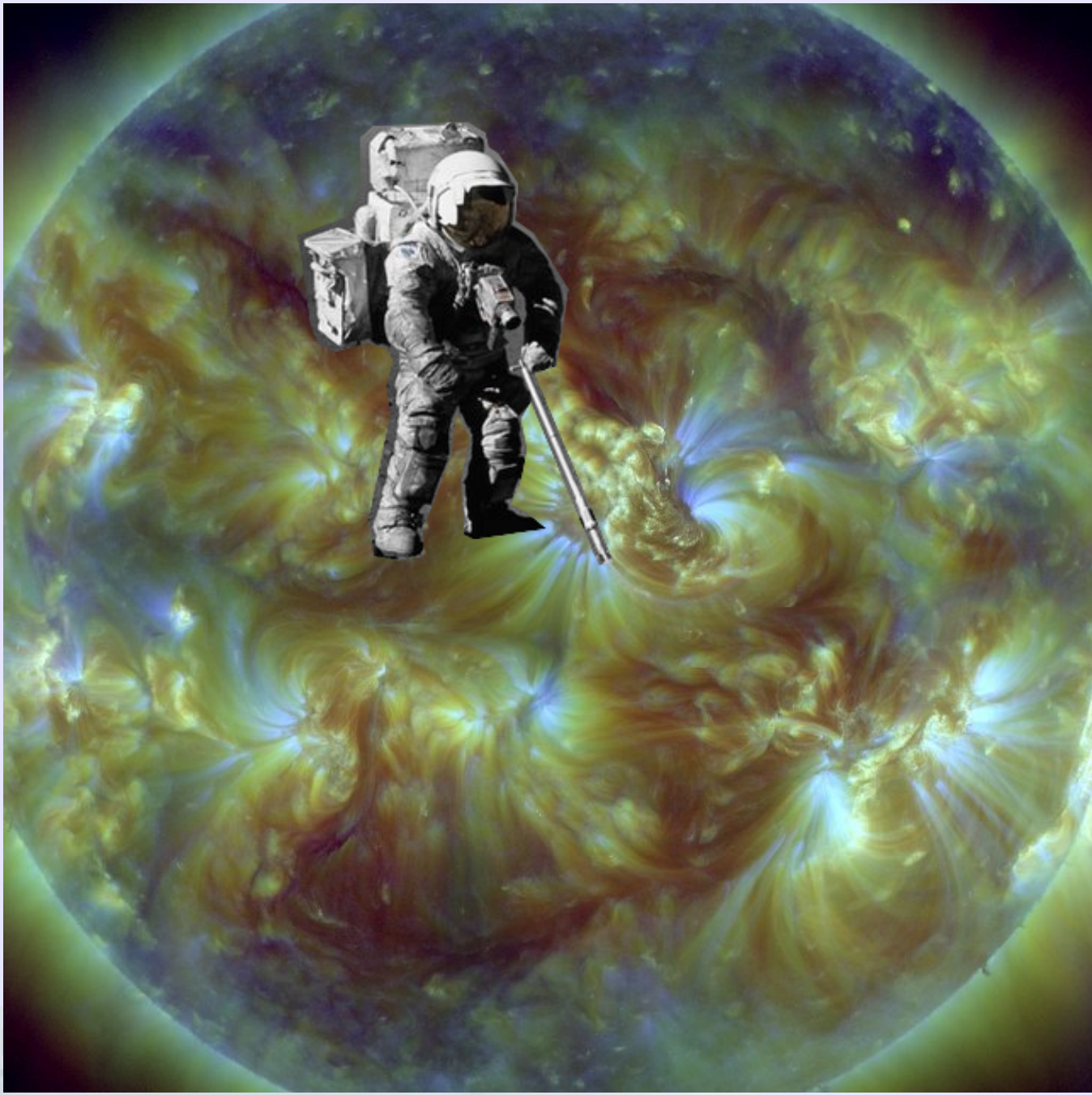
# Why this is hard, II: *remote sensing.*

**Unlike Terrestrial Weather,**

# Why this is hard, II: *remote sensing*.

**Unlike Terrestrial Weather, we will never* get *regular* in-situ measurements from the Sun.**

**This means *all* of our scientific measurements (magnetic field, density, temperature, velocities) are *indirect*.**



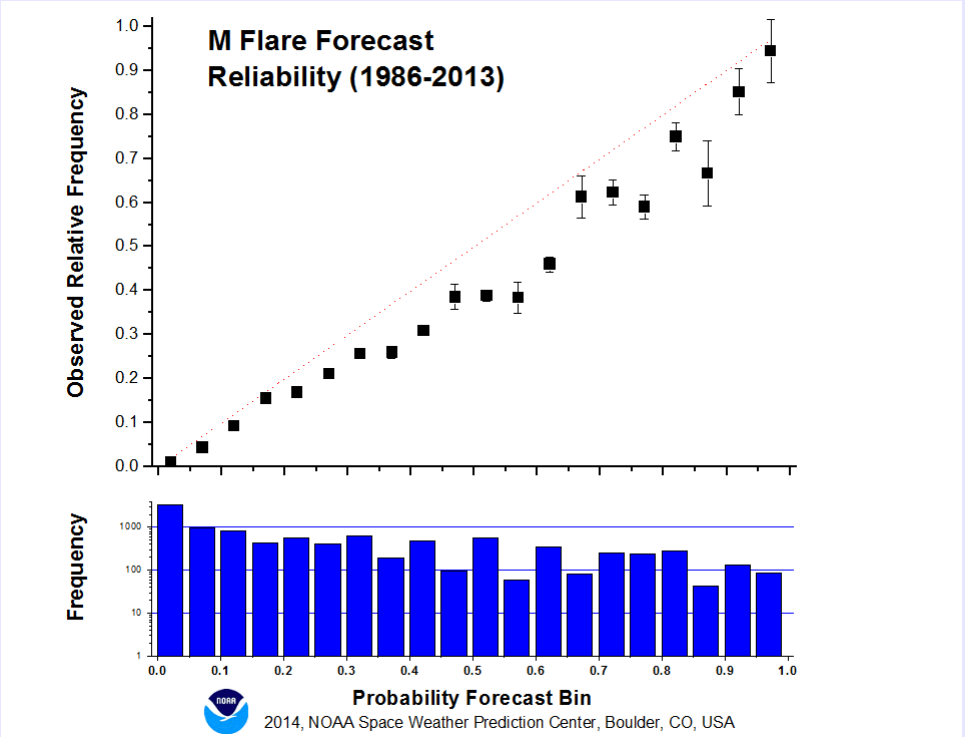
**I think I'm fairly safe saying "never" here.*

## Why this is hard, III: *Flares are rare.*

### *Corrollary: Big Flares are really rare.*

# Present Status:

- NOAA/Space Weather Prediction Center:
  - Daily forecasts for a few event definitions.
  - Many factors/inputs used in forecasts.
  - Decades of experience.
  - Forecasts used by many Centers.
  - Report Skill statistics in many forms.





*Generally fair skill reported.*

# Present Status:

*Lots of research:*

RHEA

THE UNIVERSITY OF SYDN

**Daily Solar Flare Prediction**

**Space Weather Service**

Solar Flare Prediction for Today: ..... ≥ X Class 12 % ..... M-X Class 65 % ..... ≥ C Class 100 %

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This space weather service provides automated daily predictions of the probability of a solar flare event occurring with a peak magnitude ranging from C ($10^{-6}$ W/m$^2$) to greater than X class ($10^{-4}$ W/m$^2$). The predictions are made using a statistical forecast method based on a Bayesian approach to solar flare prediction developed by Mike Wheatland of the University of Sydney.

```
Prediction made at: 2013-11-11T00:00:00.000Z
for events within 1.00 days based on 365.25 days of data
THRESH = 4.0e-06
Number of flares in year of data = 264
Maximum likelihood GAMMA = 2.050+/-0.065
Number of blocks = 8
Number of events in last block = 73
Duration of last block (days) = 10.08
Prob. of at least one flare of size M to X = 0.645+/-0.042      (1)
Prob. of at least one flare of X size or greater = 0.123+/-0.013 (1)
Prob. of at least one flare of C size or greater = 0.998+/-0.000 (1)
```

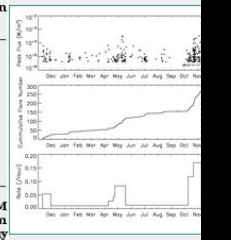
IDL code and scripts are run daily on the RHEA server at 6 AM CET, using the latest GOES 1-8 Å solar flare data obtained from NOAA. Each prediction is made for the duration of one day starting at 0000 UT of the day of the prediction, and using GOES data from the previous year (365.25 days). The text output produced by the prediction code is duplicated above, and the latest available GOES data are listed below.

Please read the disclaimer before making use of any information provided by this service.

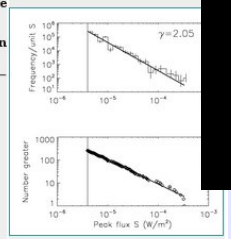
Latest Available GOES Data:

| Date | Start | Time (UT) Max | End | Peak Flux (W/m2) | Class | Active Region |
|---|---|---|---|---|---|---|
| 13/11/09 | 15:27 | 15:33 | 15:41 | 1.6e-06 | (C1.6) | 11892 |
| 13/11/09 | 15:44 | 15:52 | 15:58 | 1.4e-06 | (C1.4) | 11892 |
| 13/11/09 | 16:14 | 16:27 | 16:48 | 1.6e-06 | (C1.6) | 11894 |
| 13/11/09 | 17:00 | 17:07 | 17:20 | 1.7e-06 | (C1.7) | 11887 |
| 13/11/09 | 17:28 | 17:34 | 17:40 | 1.8e-06 | (C1.8) | 11895 |
| 13/11/09 | 18:01 | 18:04 | 18:09 | 1.3e-06 | (C1.3) | 11895 |
| 13/11/09 | 19:28 | 19:46 | 19:50 | 1.0e-06 | (C1.0) | 11895 |
| 13/11/09 | 20:39 | 20:43 | 20:46 | 1.4e-06 | (C1.4) | 11895 |
| 13/11/09 | 22:54 | 23:00 | 23:07 | 2.2e-06 | (C2.2) | 11895 |
| 13/11/10 | 01:47 | 01:52 | 02:00 | 1.5e-06 | (C1.5) | 11895 |
| 13/11/10 | 03:20 | 03:40 | 03:45 | 3.0e-06 | (C3.0) | 11895 |
| 13/11/10 | 05:08 | 05:14 | 05:18 | 1.1e-04 | (X1.1) | 11890 |
| 13/11/10 | 09:18 | 09:27 | 09:48 | 3.2e-06 | (C3.2) | 11890 |
| 13/11/10 | 12:47 | 12:52 | 12:58 | 3.1e-06 | (C3.1) | 11890 |
| 13/11/10 | 15:12 | 15:47 | 16:12 | 1.9e-06 | (C1.9) | 11895 |
| 13/11/10 | 17:08 | 17:25 | 17:33 | 1.3e-06 | (C1.3) | 11890 |
| 13/11/10 | 17:41 | 17:45 | 17:48 | 1.4e-06 | (C1.4) | 11887 |
| 13/11/10 | 18:48 | 18:55 | 18:58 | 1.3e-06 | (C1.3) | 11895 |
| 13/11/11 | 00:26 | 00:32 | 00:39 | 6.4e-06 | (C6.4) | 11890 |
| 13/11/11 | 00:43 | 00:48 | 00:51 | 7.8e-06 | (C7.8) | 11890 |

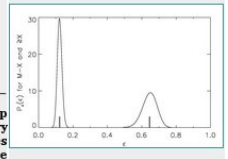
Plots generated by the code are displayed on the right. From top to bottom, the plots represent the GOES solar flare event history used to make the prediction, the size distribution of the flares and the probability function of the prediction. In addition, the reliability of the prediction method is quantified and plotted to allow a running comparison between predicted and observed values.



GOES X-Ray Flare Event History




GOES X-Ray Flare Event Distribution



X-Ray Flare Prediction

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Flare Monitor (BETA)

SOLAR FLARE PROBABILITY = 20%

| NO | CLS | M | X |
|---|---|---|---|
| 01 | BXO | 8% | 0% |
| 02 | CAO | 8% | 0% |
| 03 | CKO | 18% | 6% |
| 04 | EAO | 18% | 6% |
| 05 | FRI | 18% | 6% |
| 06 | DRO | 8% | 0% |
| 07 | DRO | 8% | 0% |

SOLAR FLARE MONITOR
Generated by ASAP 15/11/2013 15:00 UTC
http://spaceweather.inf.brad.ac.uk/ UNIVERSITY OF BRADFORD

How does flare monitor work?

Our agent program "SPIDER" connects to the SDO website every two minutes to search for the new HMI images and download them to our server.

These images are then processed using "ASAP" to automatically detect, group and then classify the

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SWRL is currently providing daily Solar Flares Forecasting and Solar Filaments Detection, w
upon work supported by NSF under Grant ATM 07-16950 and AGS-1250374, and NASA under
NNX11AQ55G. Any opinions, findings, and conclusions or recommendations expressed in
those of the author(s) and do not necessarily reflect the views of the National Science Fou

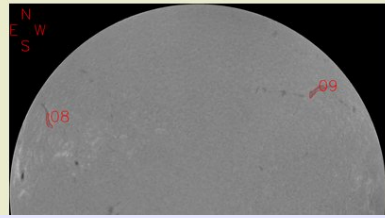
Daily Solar Flares Forecasting

| Flare Event Date | Region Number | Helicity Injection Rate (10^40 Mx^2/hr) | Total Unsigned Flux (10^20 Mx) | 0-24 hrs flare index | 24-48 hrs flare index | C-flare 0-24 hrs | C-flare 24-48 hrs | M-flare 0-24 hrs | M-flare 24-48 hrs |
|---|---|---|---|---|---|---|---|---|---|
| 2013-11-14 | 11898 | 0.04 | 33 | 0.5 | 0.9 | 13% | 13% | 3% | 3% |
| 2013-11-14 | 11897 | 1.4 | 160 | 2.5 | 3.6 | 24% | 24% | 6% | 6% |
| 2013-11-14 | 11896 | 0.52 | 66 | 1.6 | 2.4 | 20% | 20% | 5% | 5% |
| 2013-11-14 | 11895 | 0.13 | 67 | 0.8 | 1.4 | 20% | 19% | 5% | 5% |
| 2013-11-14 | 11893 | 0.6 | 106 | 1.7 | 2.5 | 22% | 21% | 6% | 5% |
| 2013-11-13 | 11898 | 0 | 26 | 0.2 | 0.3 | 10% | 10% | 3% | 2% |
| 2013-11-13 | 11897 | 2.14 | 196 | 3.1 | 4.2 | 25% | 25% | 7% | 7% |
| 2013-11-13 | 11896 | 0.2 | 65 | 1 | 1.6 | 20% | 20% | 5% | 5% |
| 2013-11-13 | 11895 | 0.61 | 68 | 1.7 | 2.5 | 20% | 21% | 5% | 5% |
| 2013-11-13 | 11893 | 0.22 | 96 | 1.1 | 1.7 | 21% | 21% | 5% | 6% |
| 2013-11-13 | 11890 | 0.54 | 148 | 1.6 | 2.4 | 23% | 23% | 6% | 6% |

For historical forecasting results, click here.
For information on the Helicity based forecasting, click here.
For information on the Flare List, click here.
For information on the Logistic Regression based forecasting, click here.

Daily Solar Filaments Detection

| ID | Area(Square Megametres) | Longitude(degrees) | Latitude(degrees) |
|---|---|---|---|
| 1 | 243.0 | -18.9 | -45.7 |
| 2 | 1141.8 | 12.3 | -37.6 |
| 3 | 438.3 | 15.3 | -31.3 |
| 4 | 806.0 | 39.5 | -28.7 |
| 5 | 6939.6 | 56.6 | -19.3 |
| 6 | 435.1 | 25.9 | -16.7 |
| 7 | 423.4 | 35.5 | -10.6 |
| 8 | 555.5 | -58.6 | 22.0 |
| 9 | 901.5 | 48.4 | 32.6 |

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Near Real Time Forecast

NOAA ARs:
12010/4
12014/5
12017/10
12018/9
12019
12020

28-Mar-14 20:47
SPAC Rote

Threat Gauge

Latest Events
NOAA: 2014/03/28 1918 ( 12017)

Near Real Time Forecast: Although HMI (Helioseismic and Magnetic Imager) data available each 45 seconds, these pages are automatically updated every 96 minutes. Forecast Text File
History of Recent Active Regions

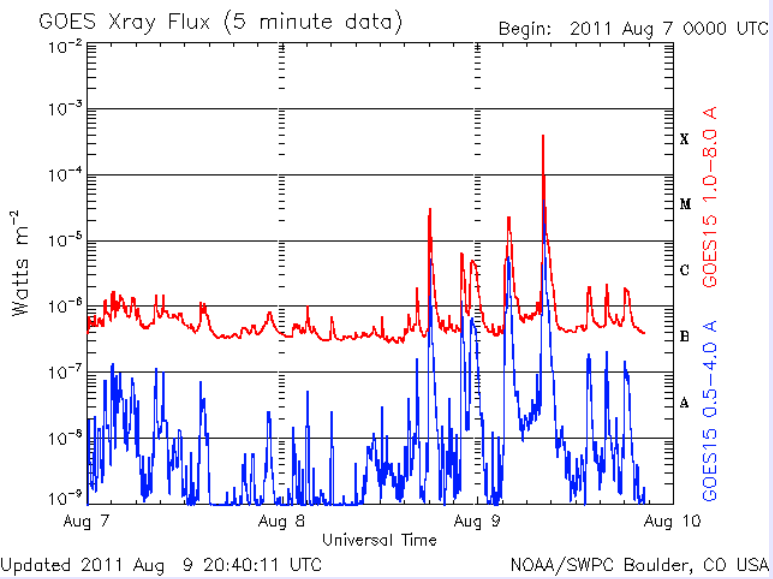
*Difficult to find skill statistics.*

# Discriminant Analysis Flare Forecasting System ("DAFFS")

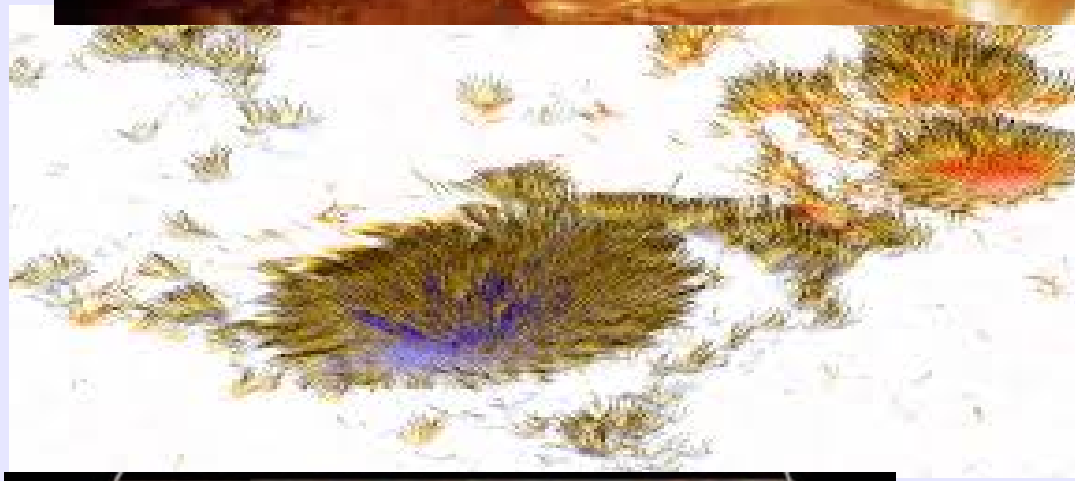
- Based on prior research, further developed under NOAA/SBIR Phase-I Feasibility study.
  - "Feasibility Study" = "Can it Work? Can it Perform?"
  - not yet a prototype: that's Phase-II (hopefully!).

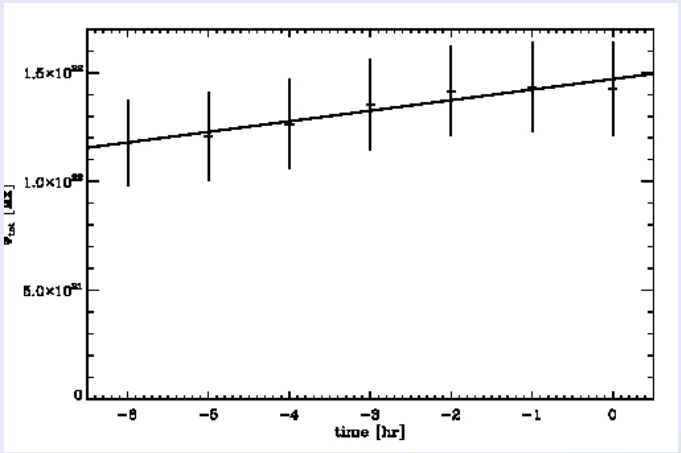
Leka & Barnes 2003a, b
Barnes & Leka 2006
Leka & Barnes 2007
Barnes et al 2007
Barnes & Leka 2008
*(see poster downstairs)*

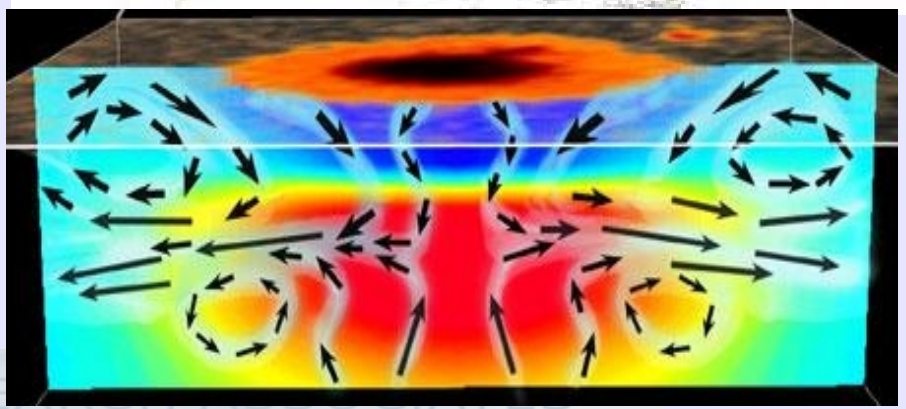
- Uses solar magnetic field observations, coronal modeling, helioseismology, evolution, and prior flare history.
- Discriminant Analysis to compute parameter-space separation between "flaring" and "flare quiet" and make forecasts.
  - Categorical or Probabalistic
- Performance Evaluation

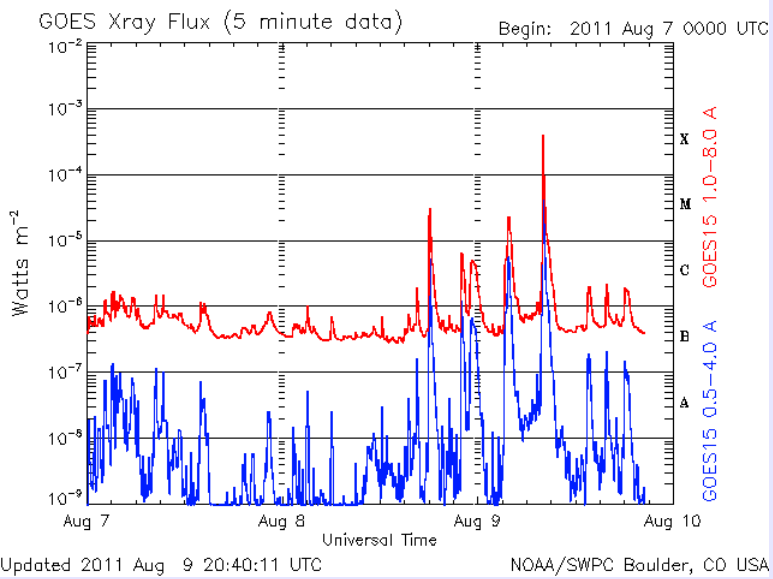



**DAFFS uses numerous "pieces" of the puzzle:**



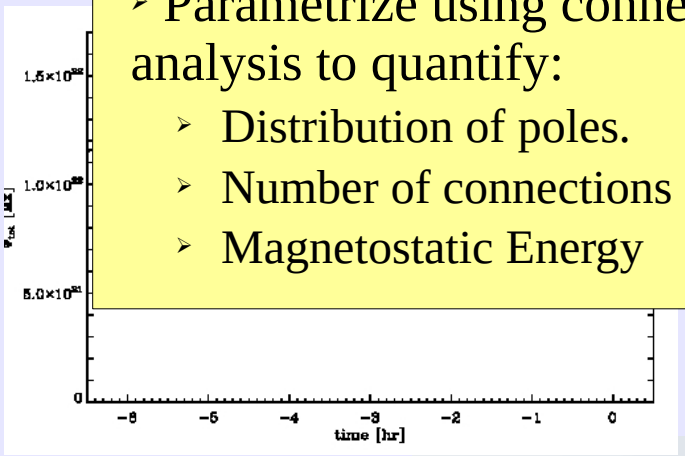


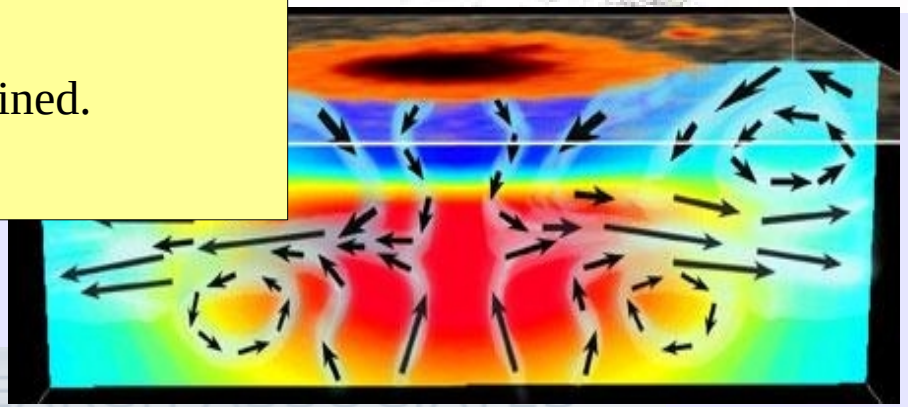



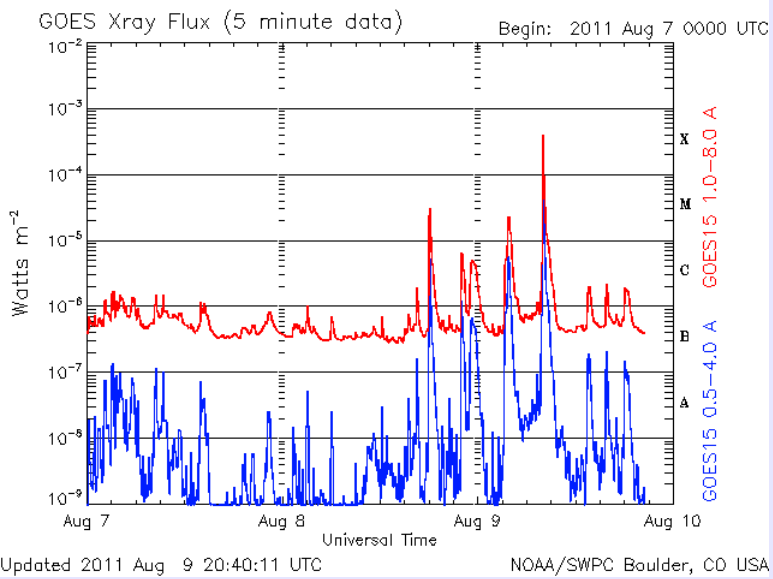



## Modeling the Coronal Magnetic Field

- Highly complex coronal magnetic fields store more energy, and may be more "ready" to flare.
- Quantify the coronal field topology to:
  - Indicate how much energy is available.
  - Indicate readiness for magnetic reconnection.
- Parametrize using connectivity matricies & moment analysis to quantify:
  - Distribution of poles.
  - Number of connections and the flux contained.
  - Magnetostatic Energy

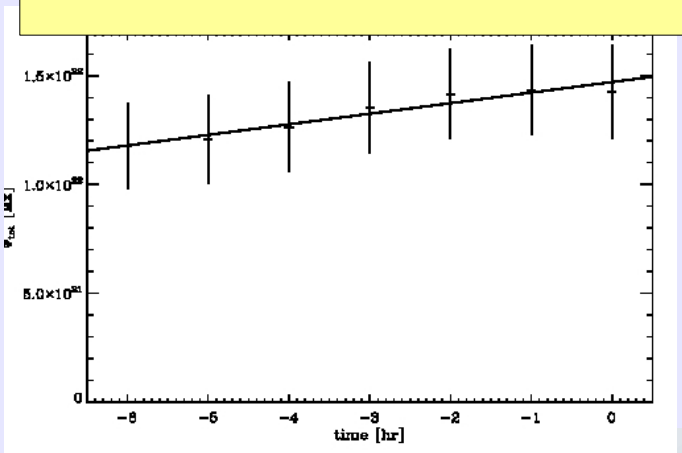


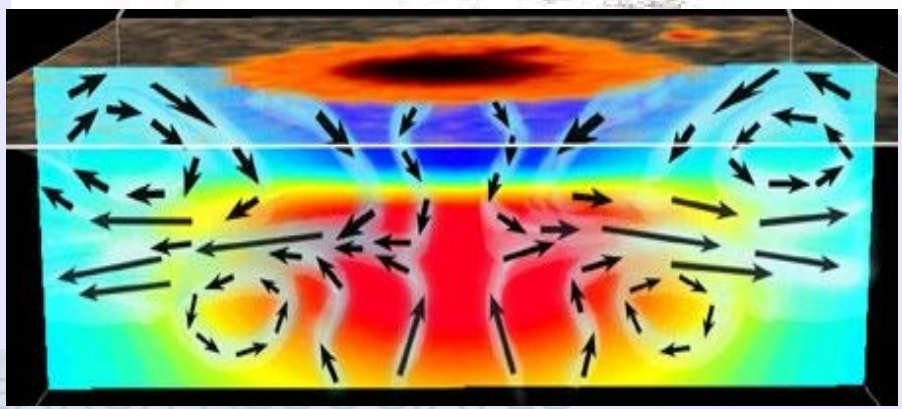



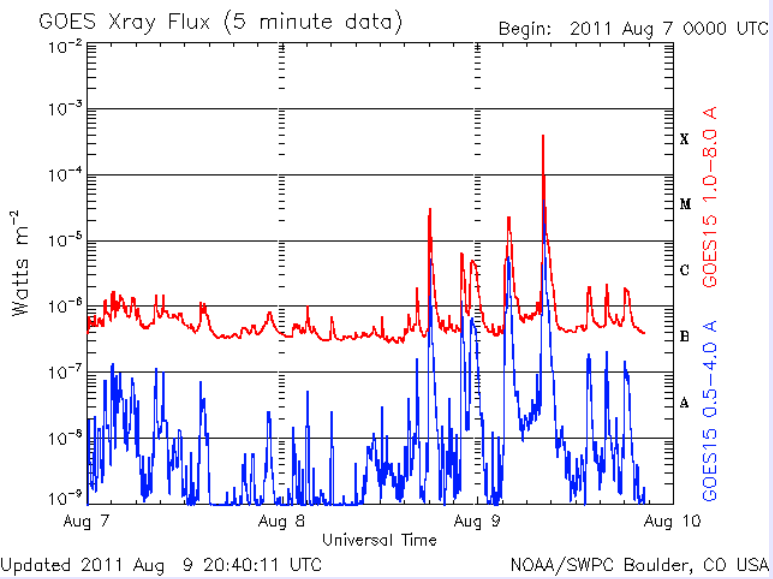



## Vector Magnetic Field Maps:

- Quantify indicators of flare productivity.
  - Magnetic stress and stored energy.
- Parametrize using moment analysis to describe:
  - Magnetic Field Distributions
  - Electric Current Distributions
  - Complexity

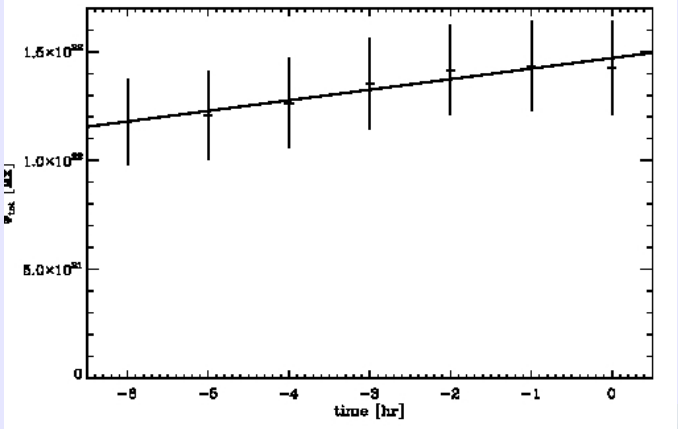


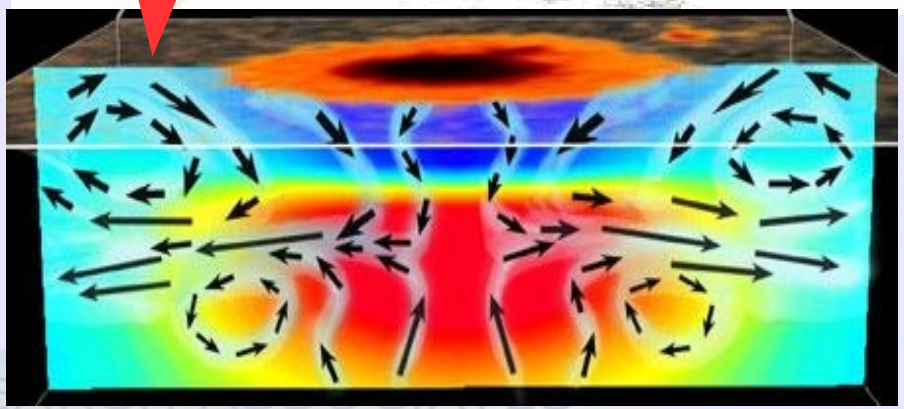



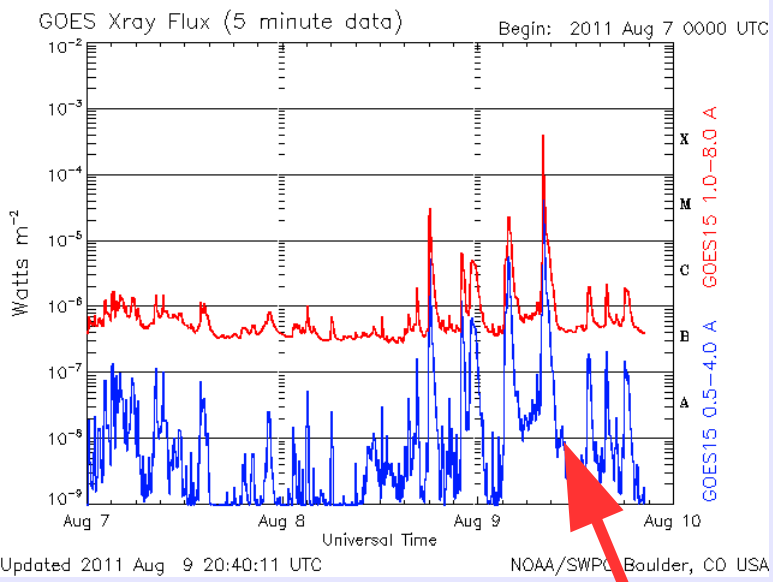



## Local Helioseismology

- Plasma flows *under* active regions may indicate energy generation and storage.
- May also indicate imminent appearance of new magnetic flux.
- Helioseismic Holography
  - Derive and parametrize
    - plasma divergence, flow vorticity.
    - different depths 0.75 – 10 Mm below the surface.

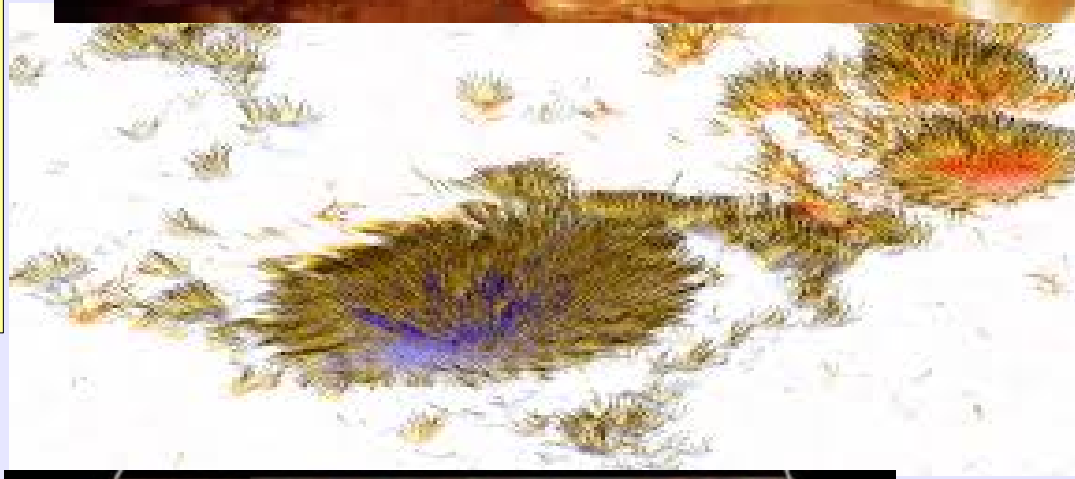


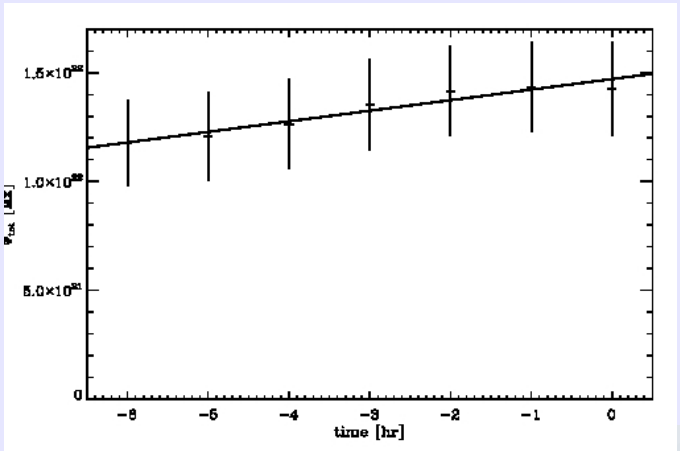



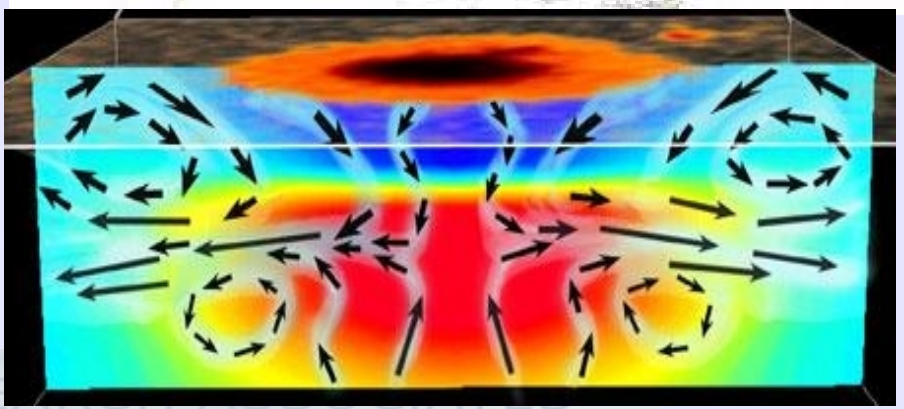


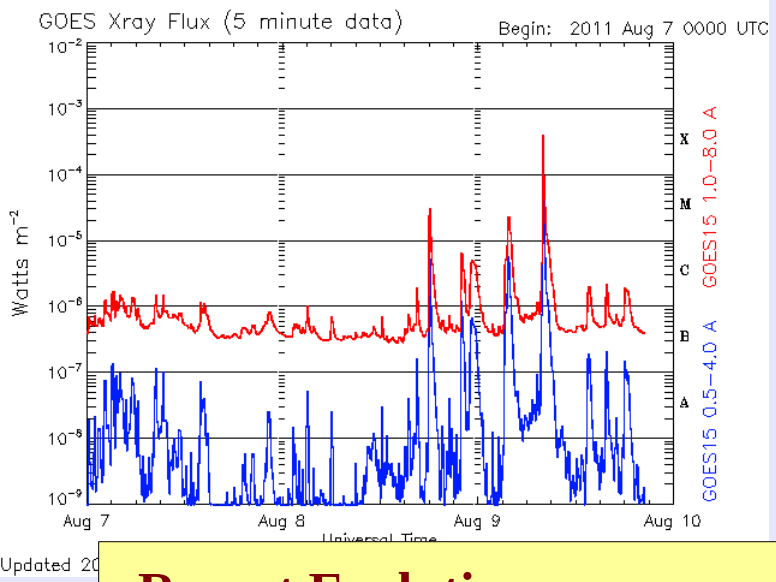

## Prior Flare History

- Previous flaring often best indicator of future flaring, especially for larger flares.
- Parametrize:
  - Number, Size of Flares
  - Flaring Rate



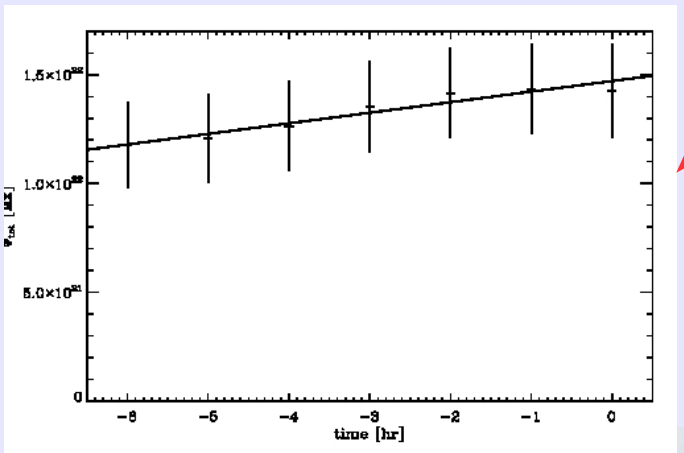


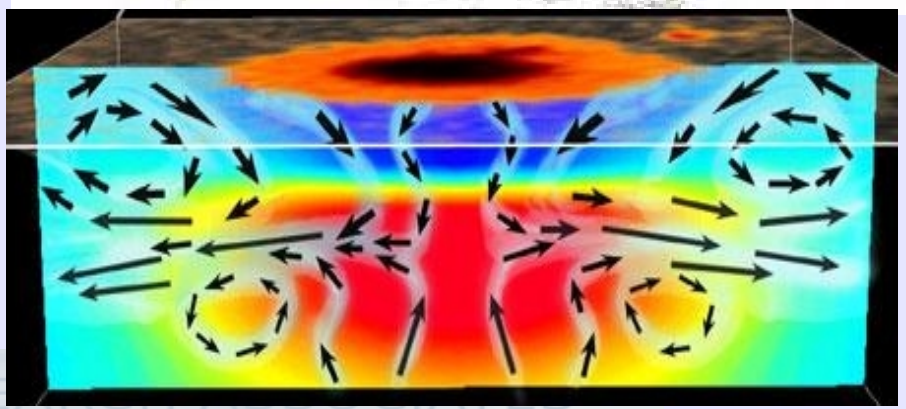





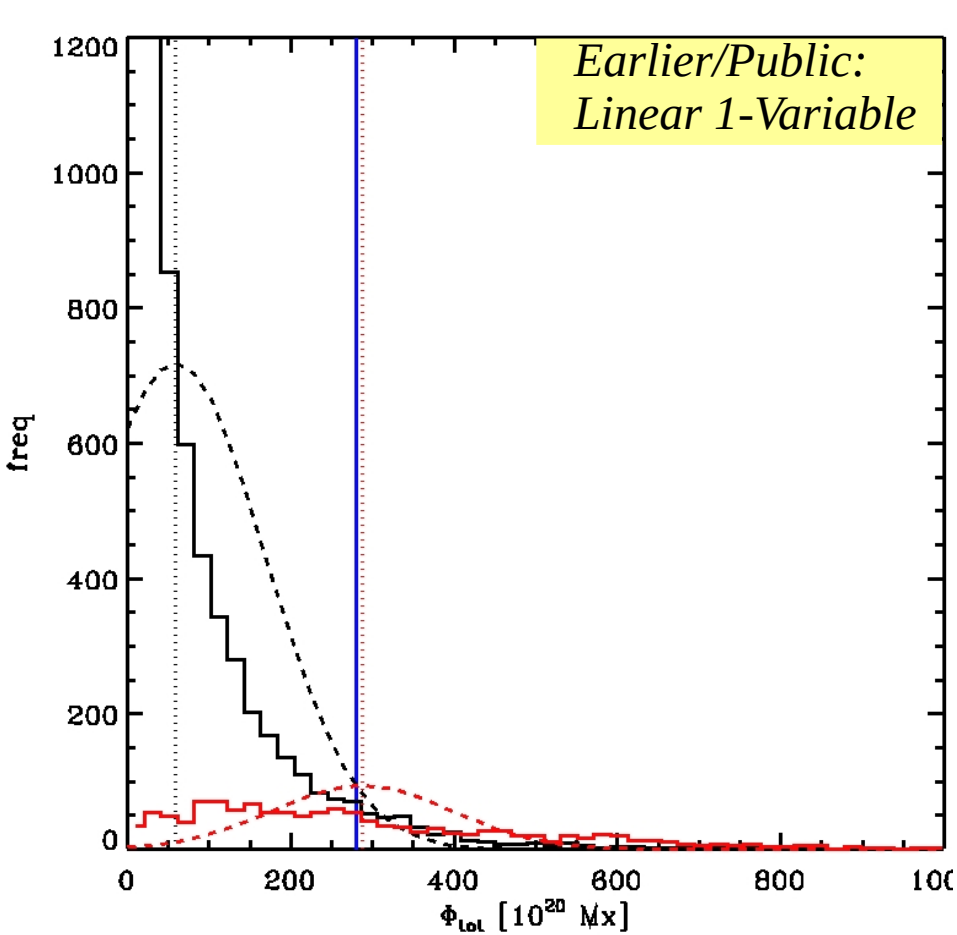

## Recent Evolution

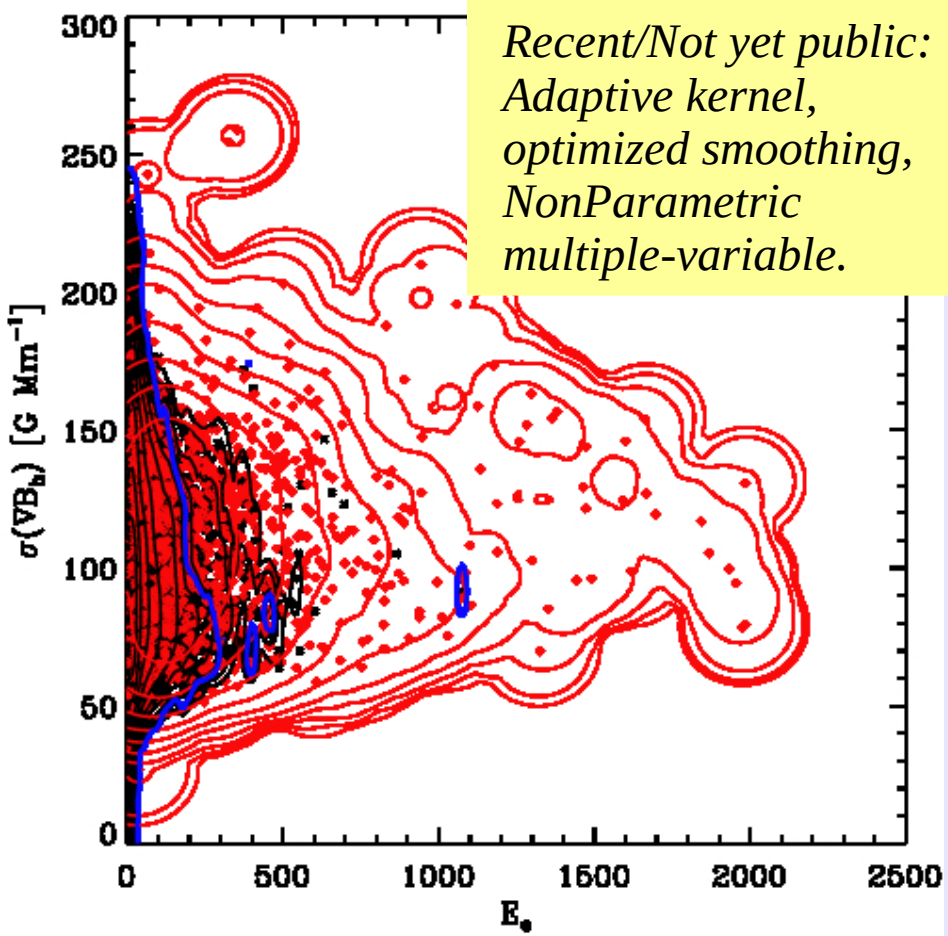
- Quickly-evolving active regions are often flare-productive.
  - Growing, becoming more complex, etc.
- Many computed parameters (from coronal modeling, magnetic field analysis, flaring history) are also tracked for their recent evolution.
- Recent evolution included in DAFFS



- **Discriminant Analysis** to compute parameter-space separation between "flaring" and "flare quiet"
  - New measurement (new active region) is predicted to flare/not according to its location relative to the discriminant function.
  - **Many improvements** since 2003--2008 series of papers.



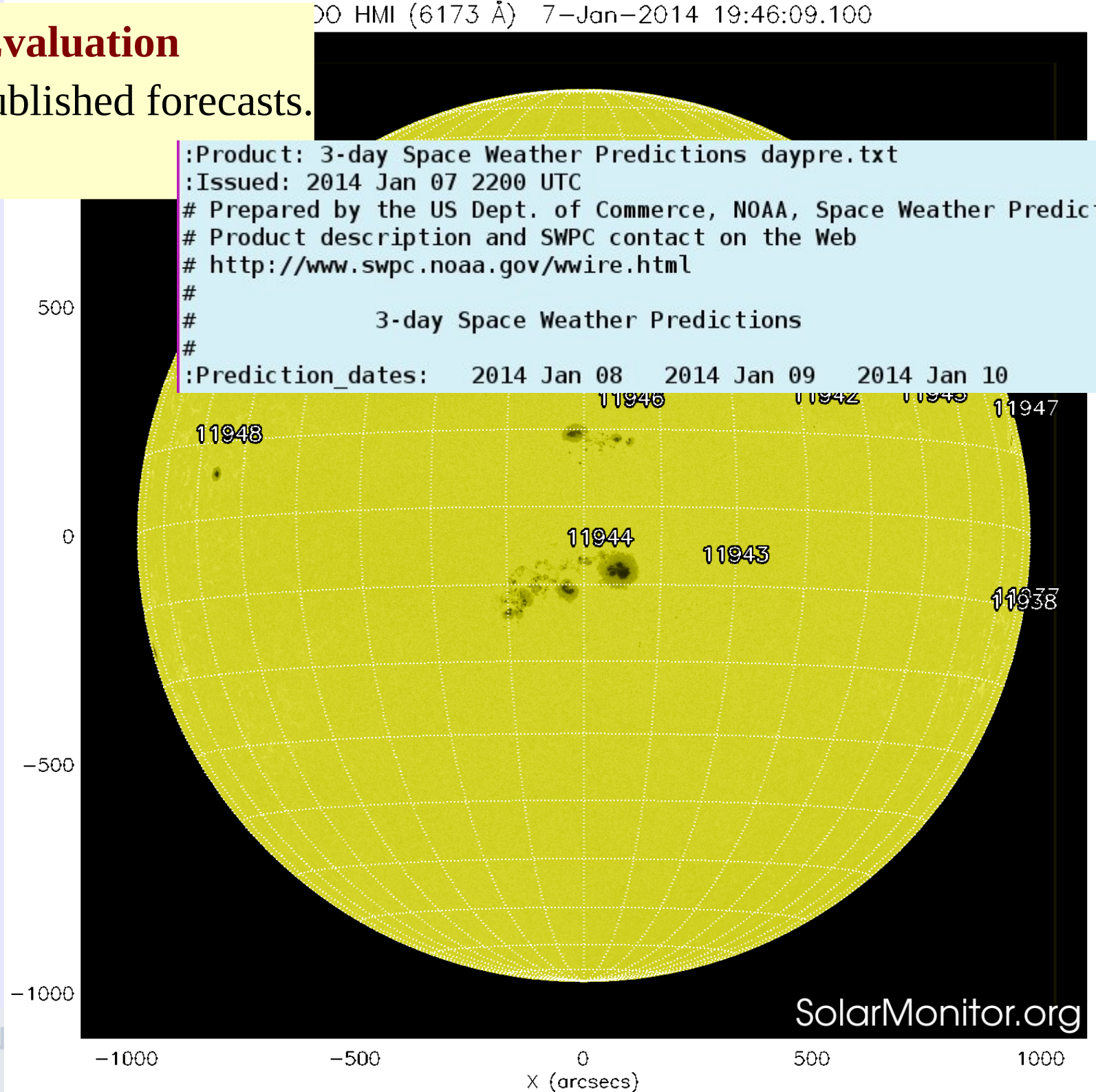




— **flaring**/— **non-flaring histograms**
- - - **parametric PDFs**
— **DF 50% boundary**

• **flaring**/ • **non-flaring points**
—/— AK/OS/NPDA PDFs
— **DF 50% boundary**

## Performance Evaluation

- Match NOAA published forecasts.

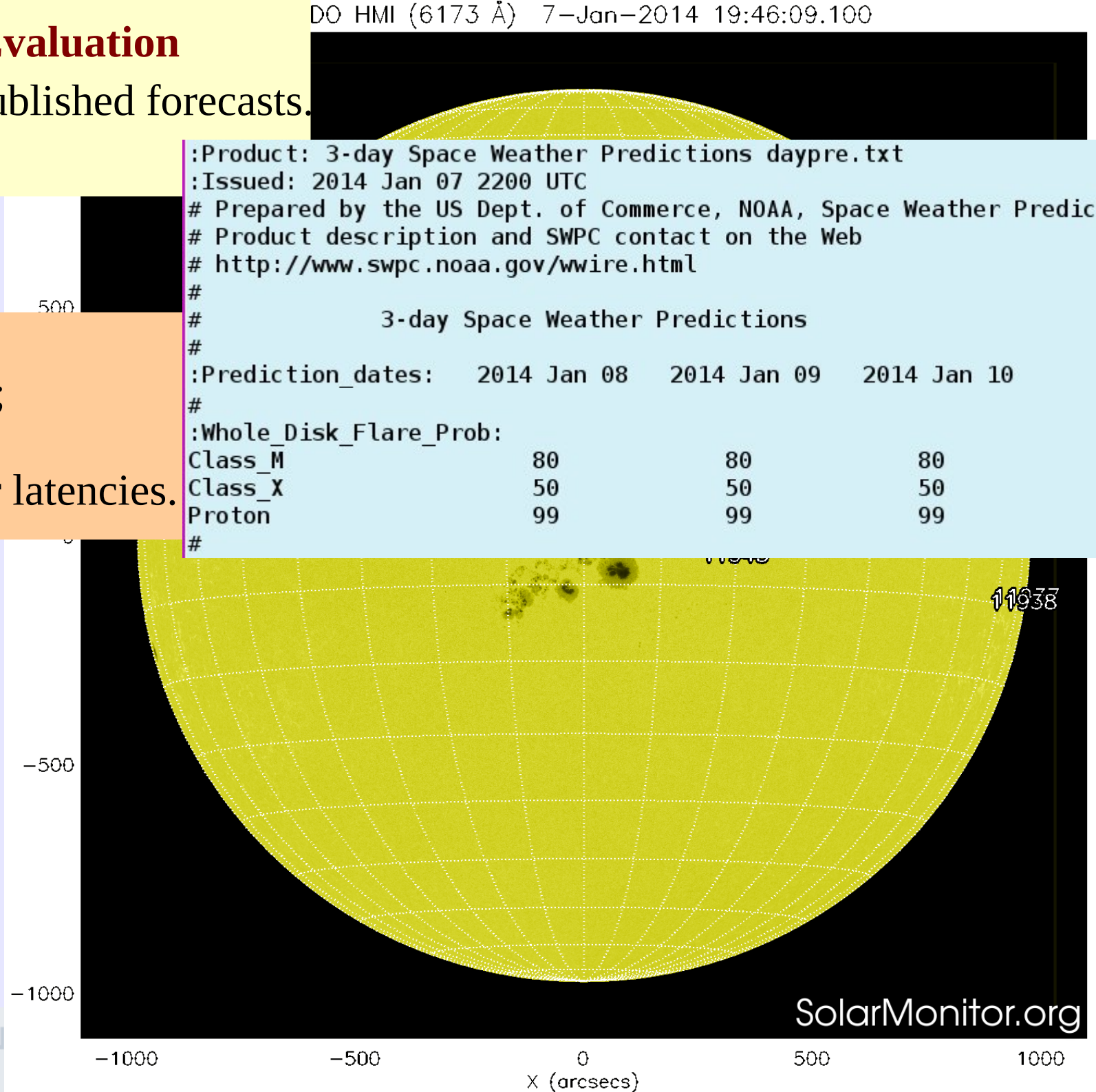


## Performance Evaluation

- Match NOAA published forecasts.
- Two “flavors”:

- ***Full-disk***
  - M1.0+, X1.0+;
  - 24hr validity;
  - 0hr, 24hr, 48hr latencies.

```
:Product: 3-day Space Weather Predictions daypre.txt
:Issued: 2014 Jan 07 2200 UTC
# Prepared by the US Dept. of Commerce, NOAA, Space Weather Predic
# Product description and SWPC contact on the Web
# http://www.swpc.noaa.gov/wwire.html
#
#              3-day Space Weather Predictions
#
:Prediction_dates:   2014 Jan 08   2014 Jan 09   2014 Jan 10
#
:Whole_Disk_Flare_Prob:
Class_M                    80             80             80
Class_X                    50             50             50
Proton                     99             99             99
#
```

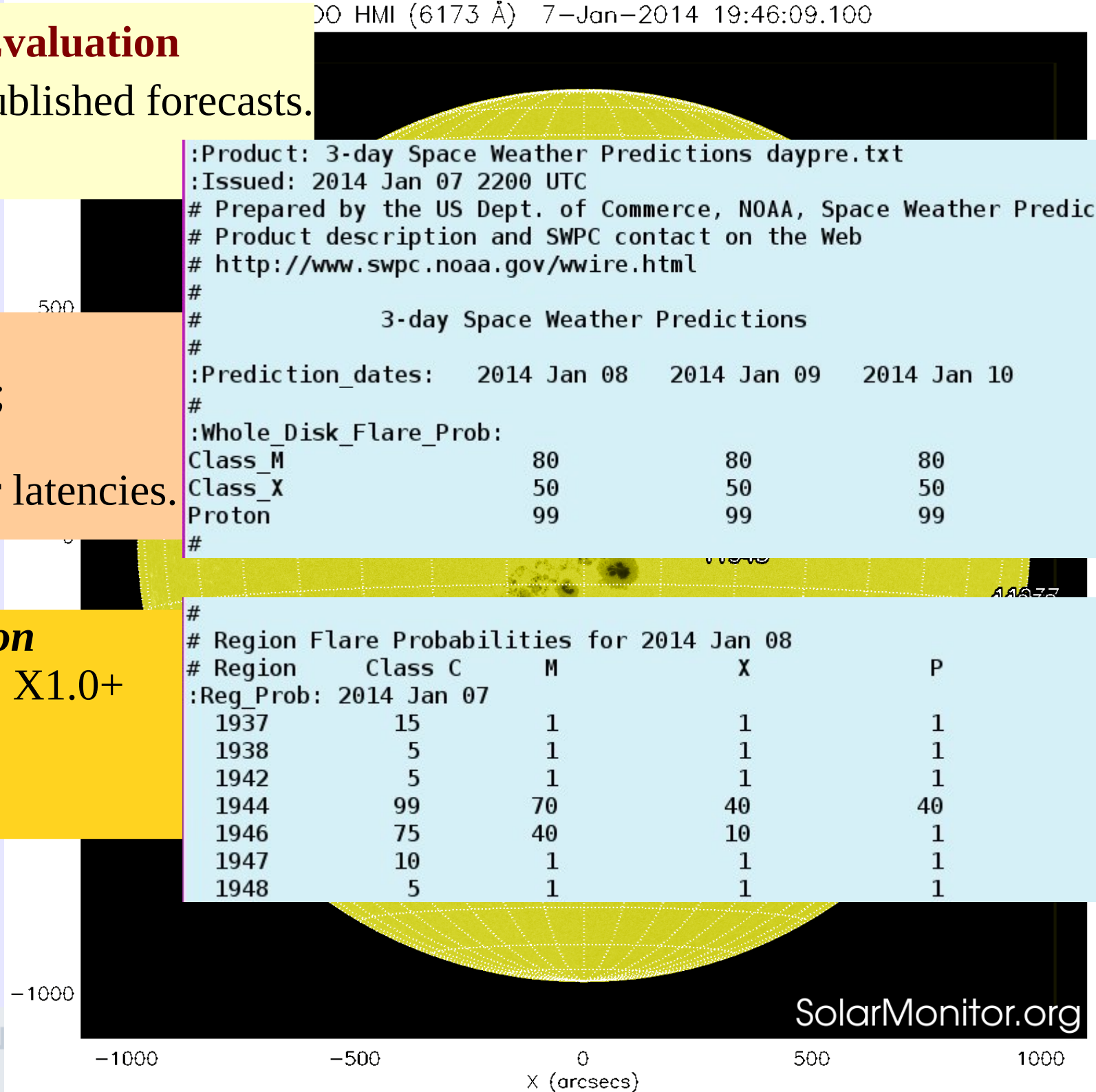


## Performance Evaluation

- Match NOAA published forecasts.
- Two “flavors”:

- ***Full-disk***
  - M1.0+, X1.0+;
  - 24hr validity;
  - 0hr, 24hr, 48hr latencies.

- ***Region-by-Region***
  - C1.0+, M1.0+, X1.0+
  - 24hr validity,
  - 0hr latency

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#              3-day Space Weather Predictions
#
:Prediction_dates:   2014 Jan 08   2014 Jan 09   2014 Jan 10
#
:Whole_Disk_Flare_Prob:
Class_M                    80            80            80
Class_X                    50            50            50
Proton                     99            99            99
#
```

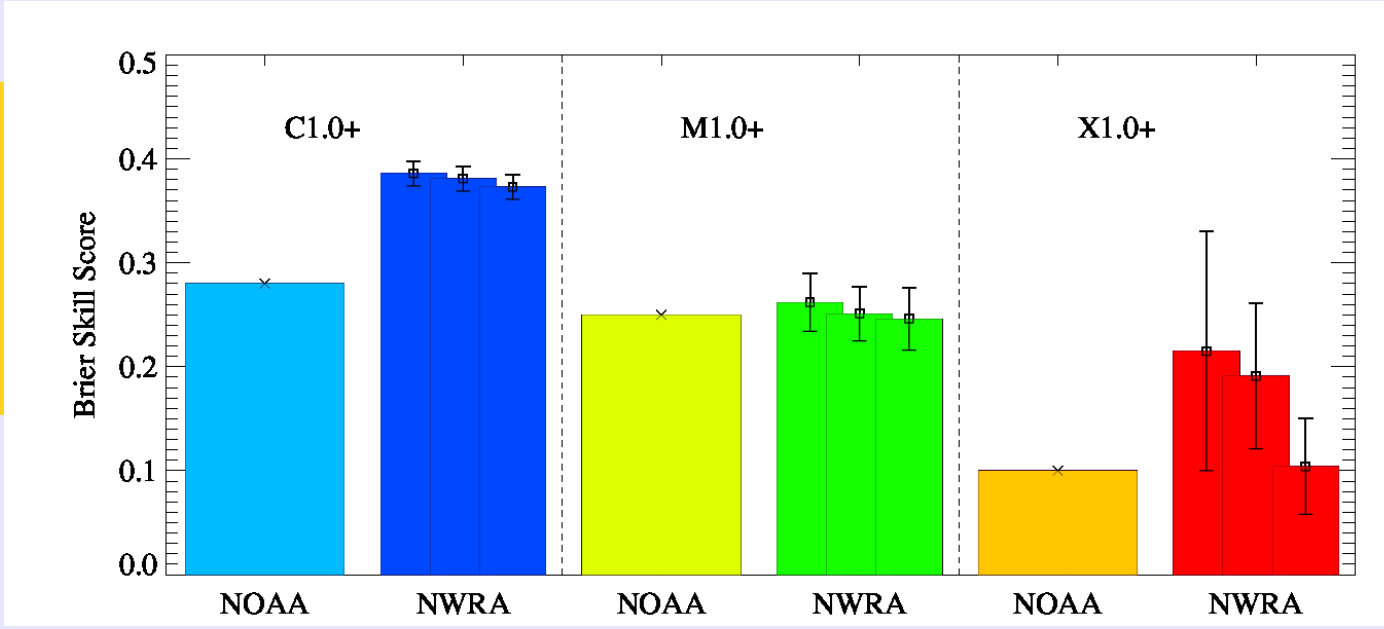
```
#
# Region Flare Probabilities for 2014 Jan 08
# Region     Class C      M             X             P
:Reg_Prob: 2014 Jan 07
  1937          15          1             1             1
  1938           5          1             1             1
  1942           5          1             1             1
  1944          99         70            40            40
  1946          75         40            10             1
  1947          10          1             1             1
  1948           5          1             1             1
```

- **Performance Evaluation** – other details.
  - Over (most of) Solar Dynamics Observatory mission
    - 01 May 2010 – 30 November 2013.
    - 9,073 NOAA Active Region samples;
    - 14,929 SDO/HMI Active Region "Patch" samples;
    - 1,310 days.
    - **3,770 C-class flares**, **335 M-class flares**, **25 X-class flares.**
  - Compare Brier Skill Scores and Reliability Plots
    - $BSS = 1.0 - MSE/MSE_{ref}$
      - BSS = 0.0 : No skill
      - BSS < 0.0 : worse than no skill.
      - BSS = 1.0 : perfect forecast.
  - NOAA archive forecasts.
    - Supplied by NOAA/SWPC *(courtesy C. Balch)*
    - No uncertainties available.
  - DAFFS results:
    - The top few scoring options are shown.
    - Uncertainties via bootstrap methods.

- ***Region-by-Region***
  - C1.0+, M1.0+, X1.0+
  - 24hr validity,
  - 0hr latency

*NWRA approach generally demonstrates higher Brier Skill Scores.*

- smaller error bars with higher sample sizes.

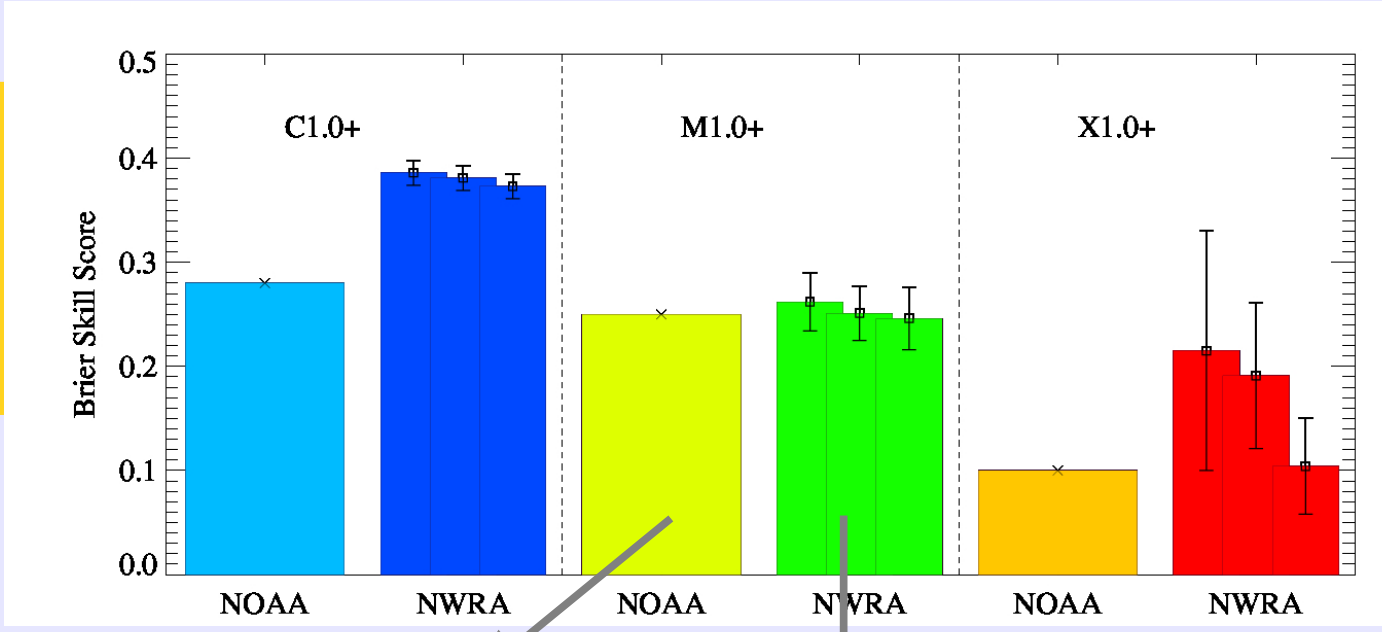


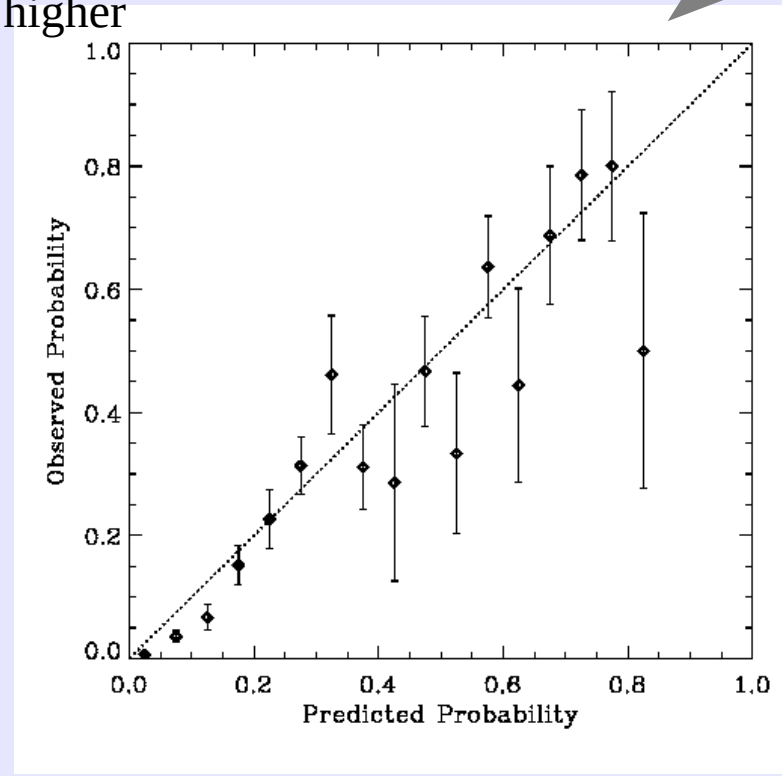
- ***Region-by-Region***
  - C1.0+, M1.0+, X1.0+
  - 24hr validity,
  - 0hr latency

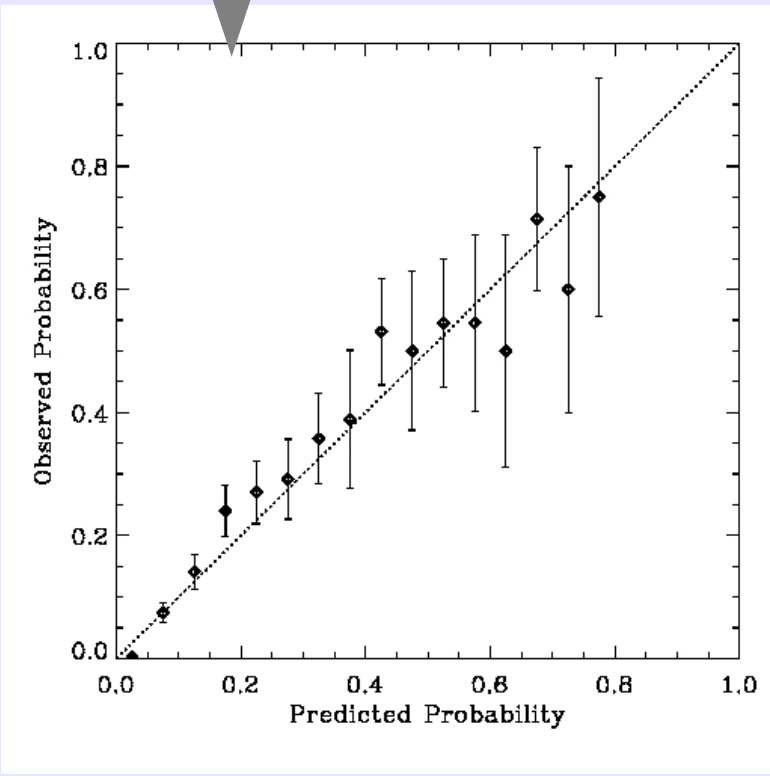
*NWRA approach generally demonstrates higher Brier Skill Scores.*

- smaller error bars with higher sample sizes.

- Where BSS are similar, reliability plots show improvement.



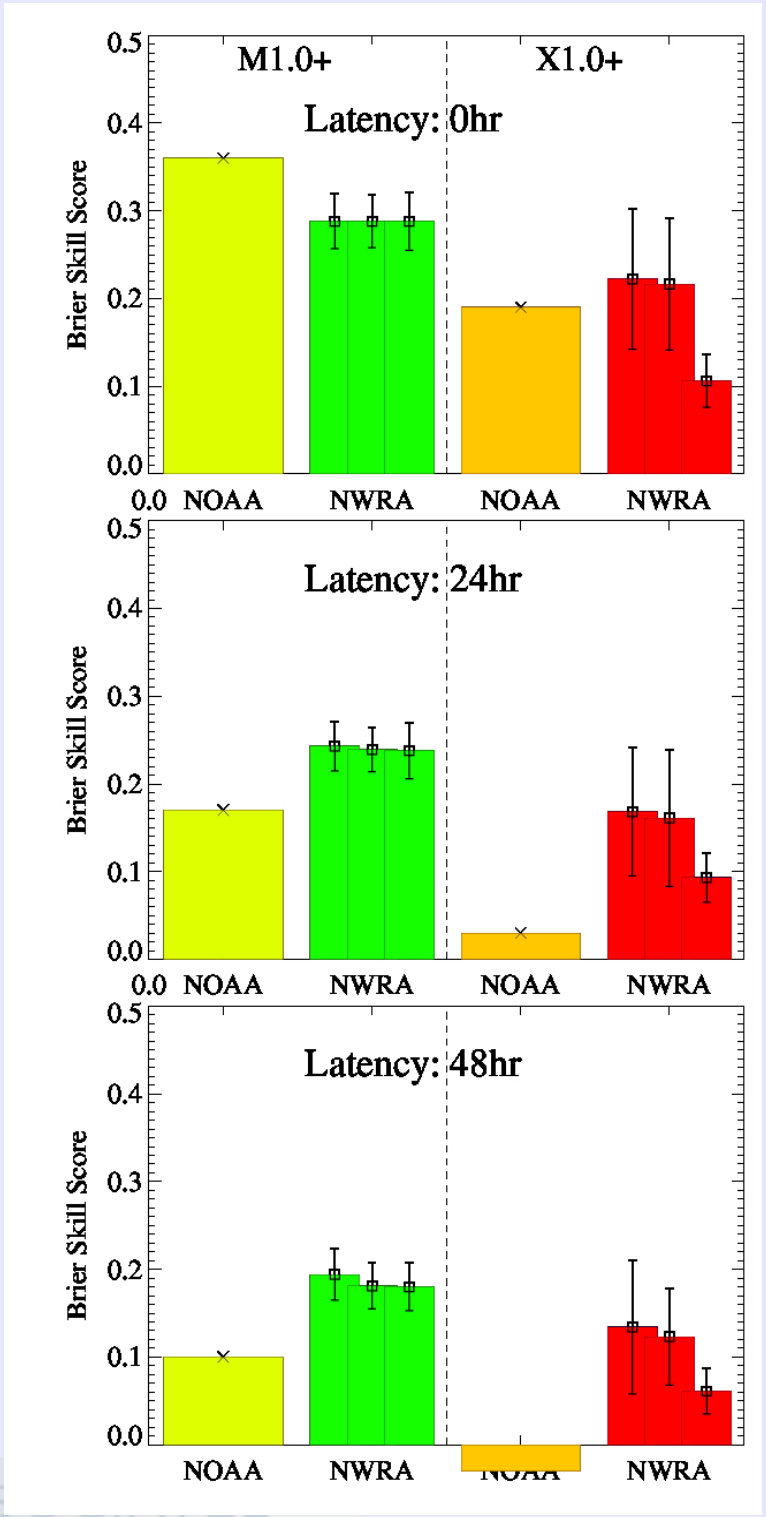



- ***Full-disk***
  - M1.0+, X1.0+;
  - 24hr validity;
  - 0hr, 24hr, 48hr latencies.

*NWRA approach generally demonstrates higher Brier Skill Scores.*

- Especially for larger events @ longer latencies (2- and 3-day forecasts).



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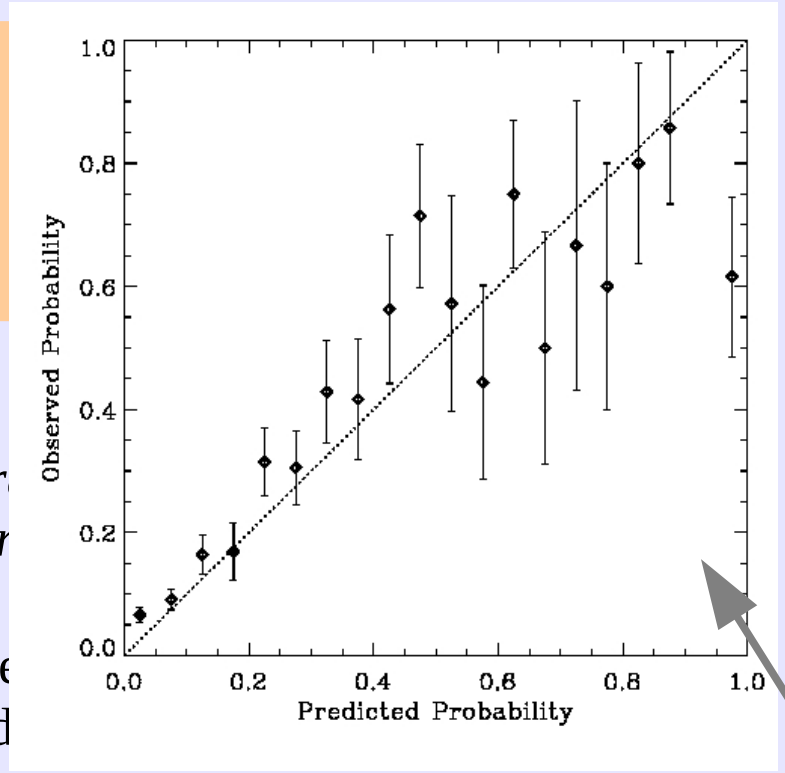
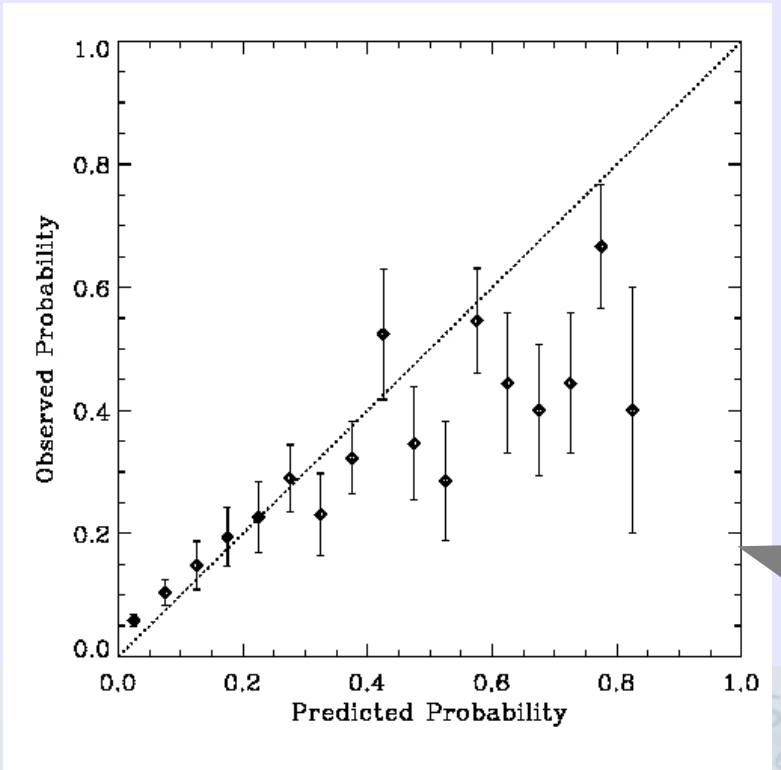
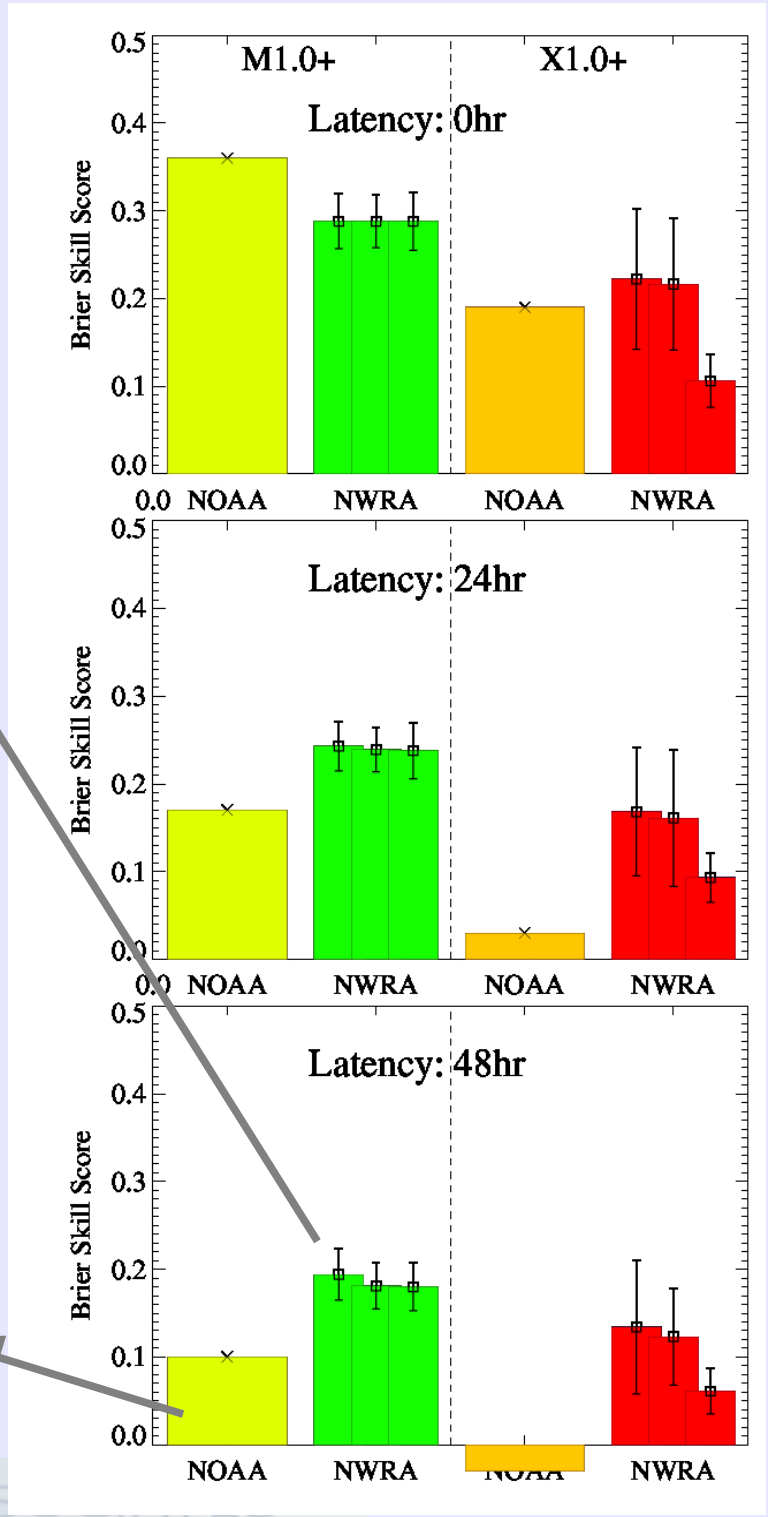


# Summary:

- **Forecasting Solar Flares is not easy.**
  - Rare Events
  - Poorly-understood physics
  - Remote Sensing

- **NOAA/SWPC does pretty well!**
  - ***but DAFFS can do better,*** for:
    - Region-by-Region forecasts.
    - Larger events, especially @ longer-range forecasts.
    - Lots of room (and options) for improvement*.

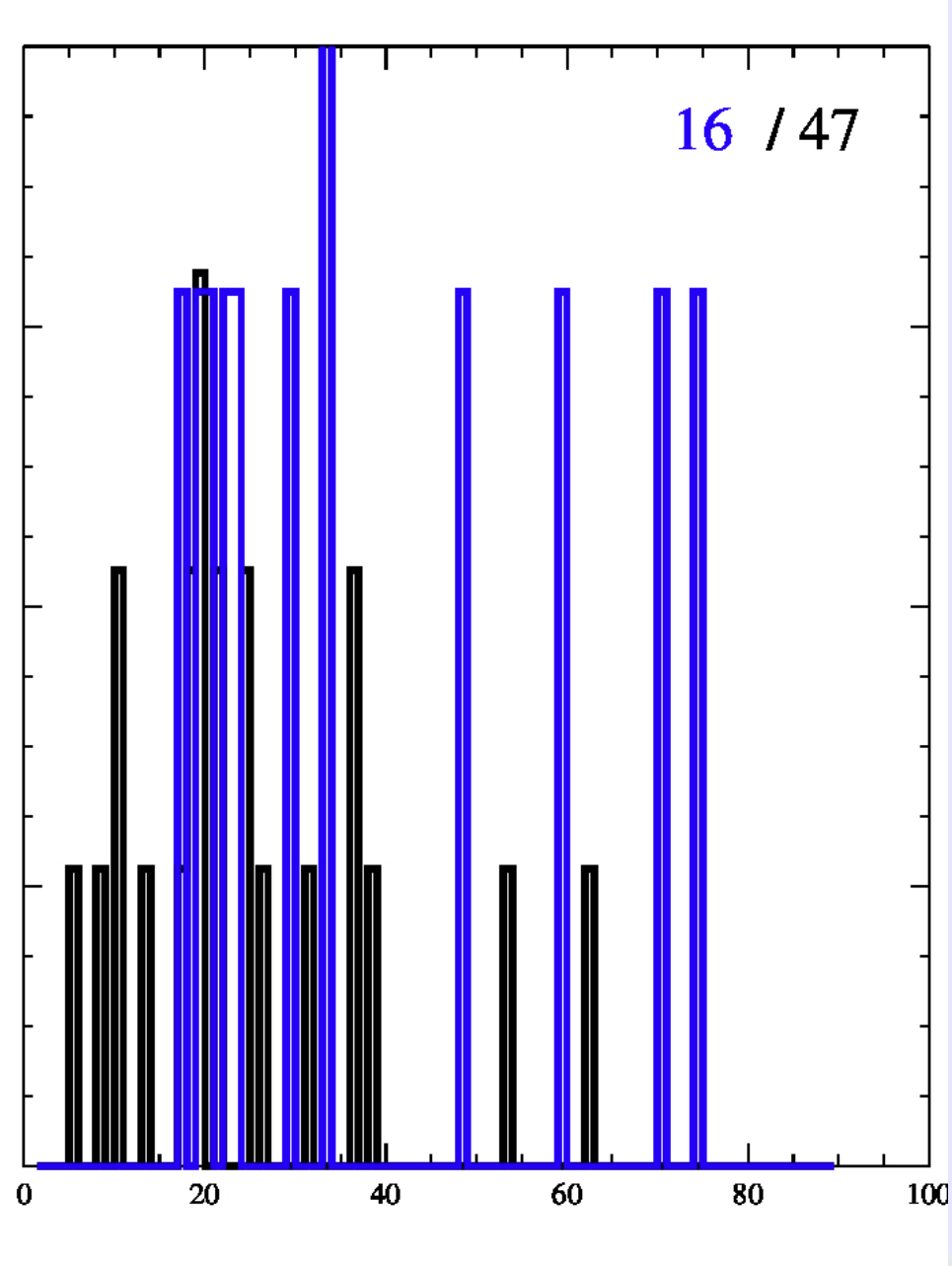
- ***Things people in this room should be aware of:***
  - *Skill reporting* can be critical, and tricky*.
  - No* *operational* data source for this or most other methods.

* come by poster for details and discussion!

# Extra Slides

# Why this is hard, II: *Flares are rare.*

## *Corrollary: Big Flares are really rare.*



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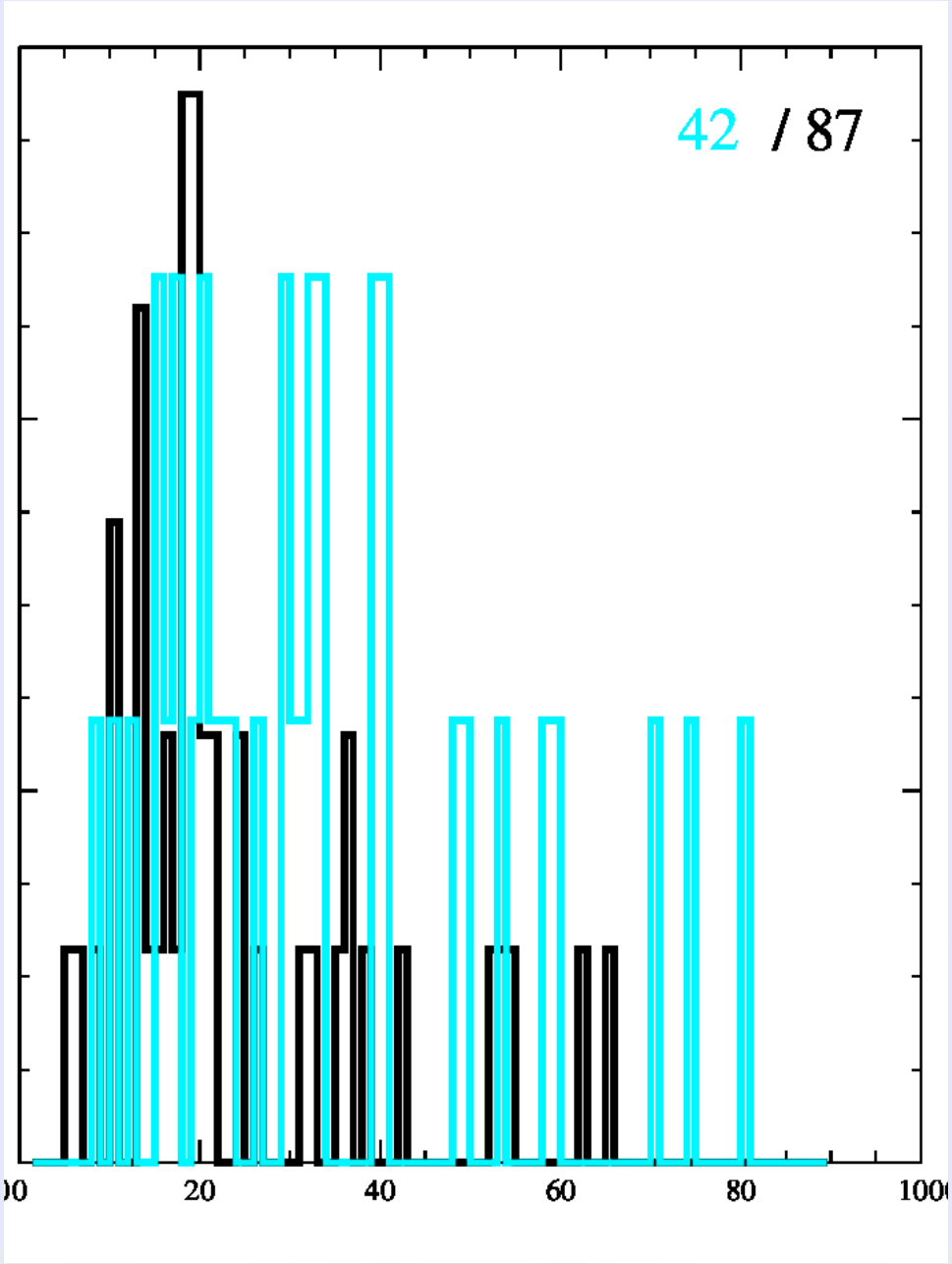

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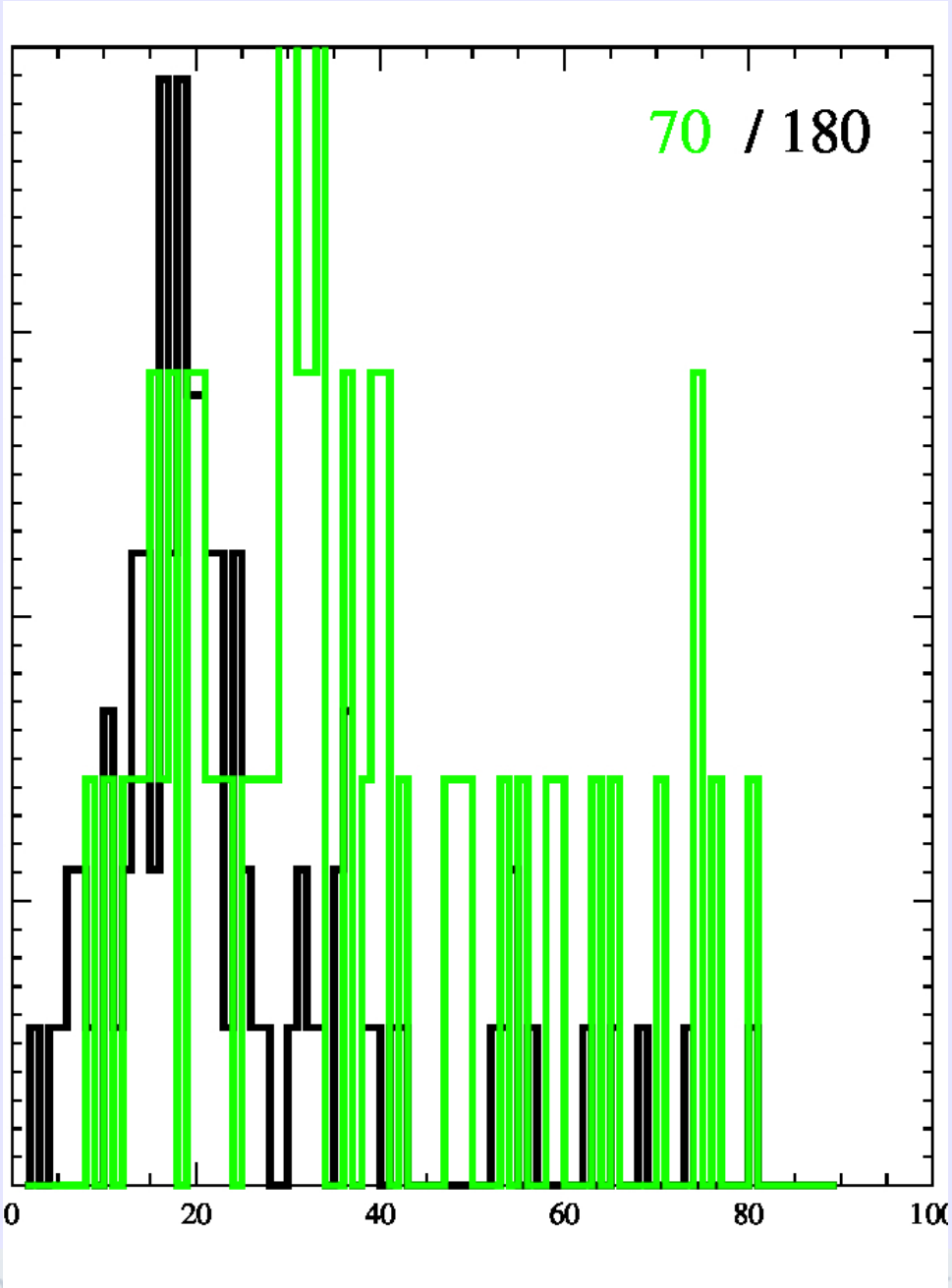

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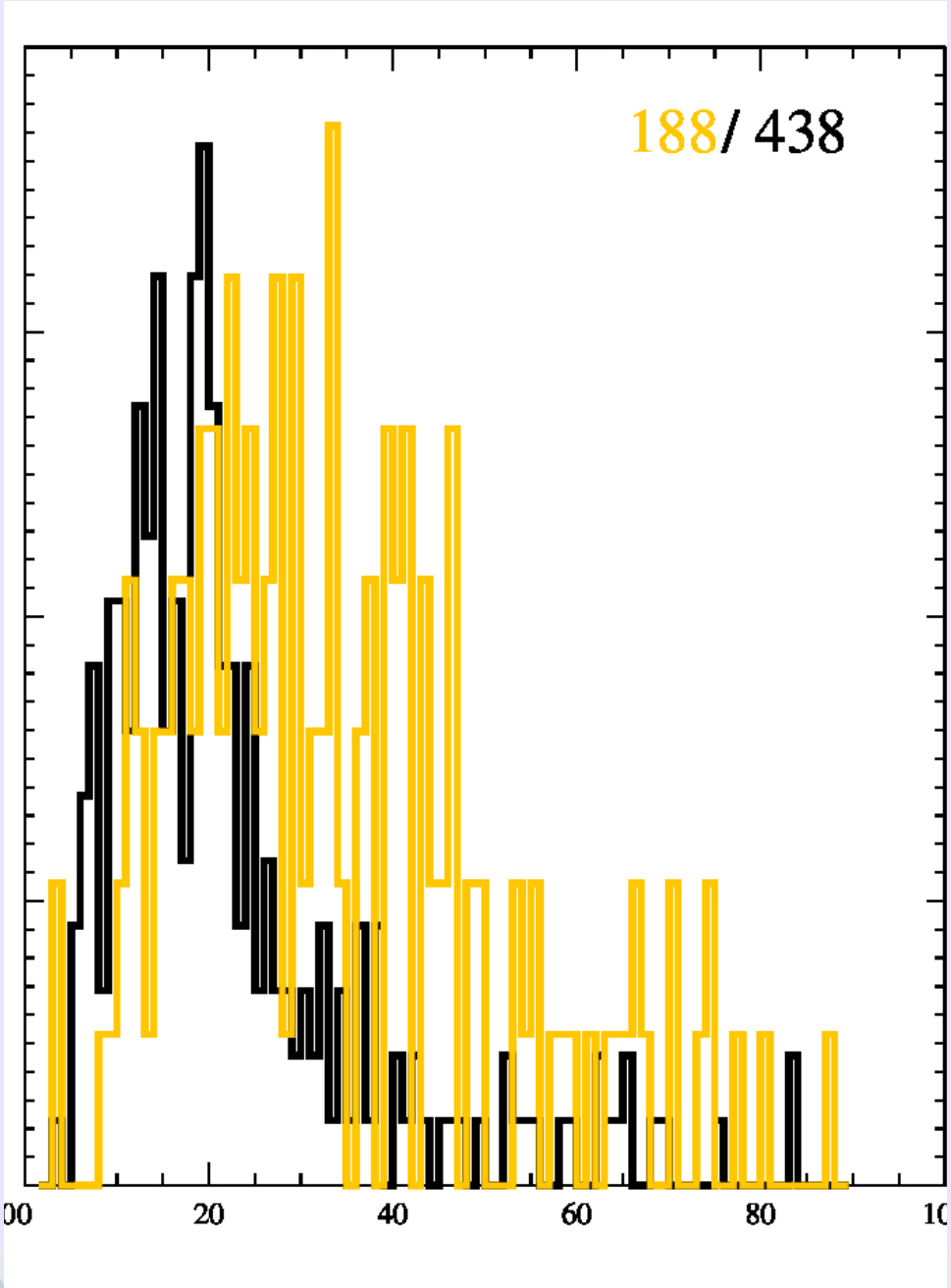

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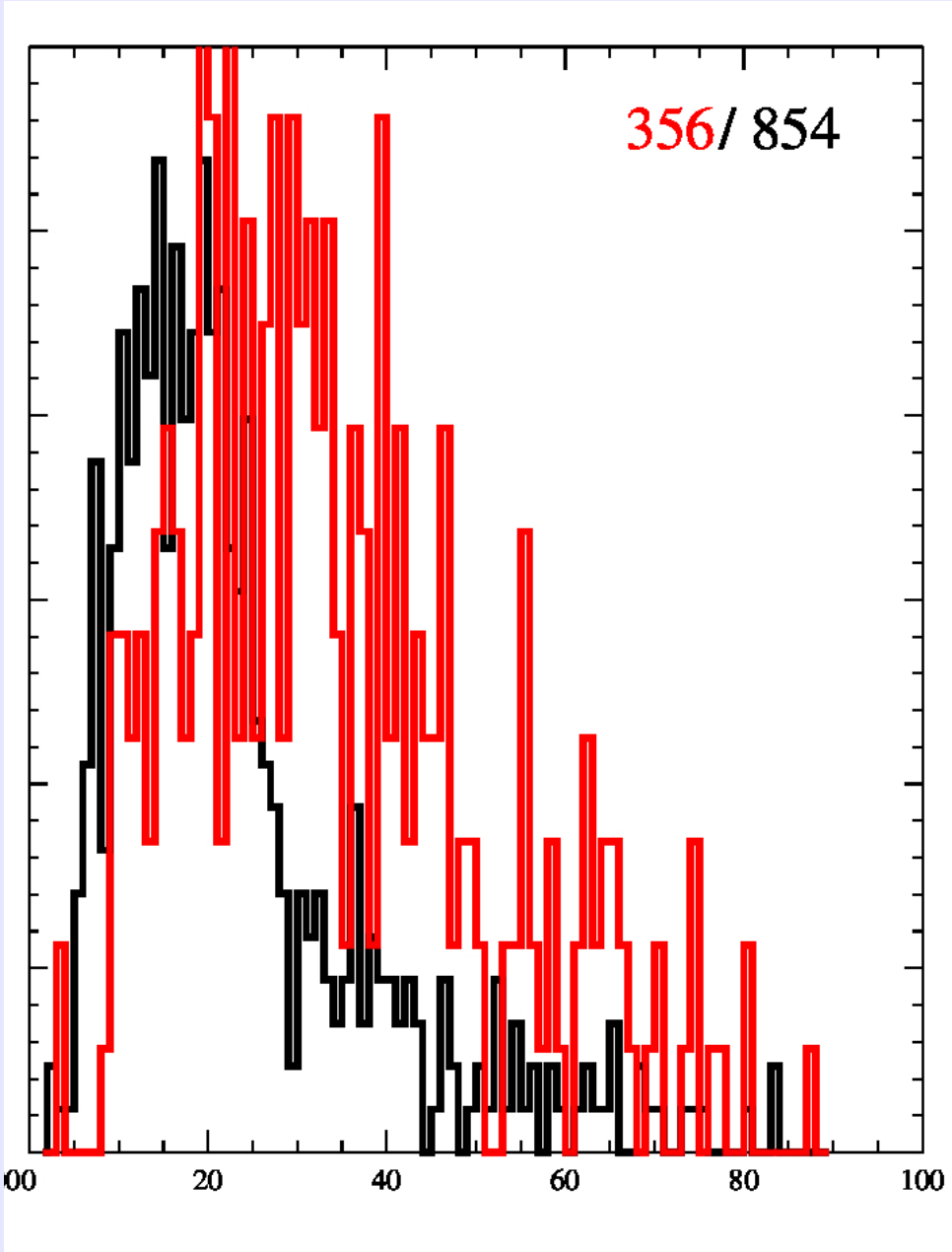
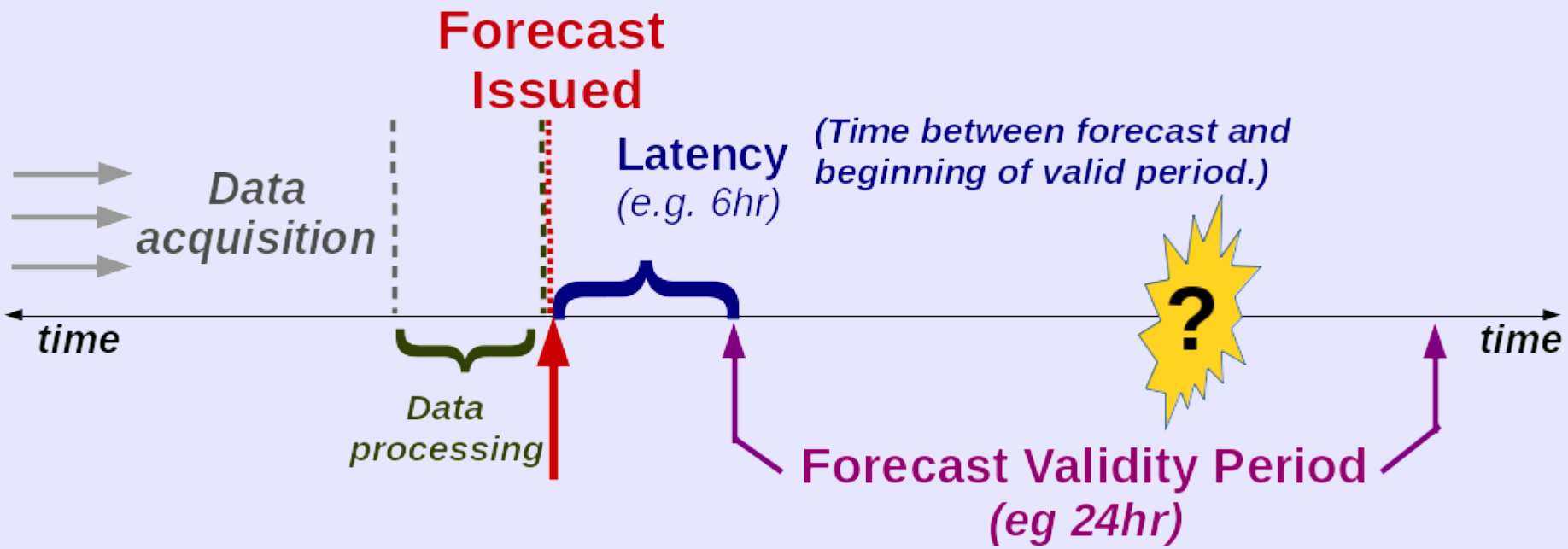


# Why this is hard, IV: *Different customer needs.*

- Requirements for Event Types

  (only large flares, only Geo-Effective SEPs, etc.)
- Required/Acceptable Forecast Windows, Frequency, Latencies
- Other concerns (False Alarms, *etc.*)



***Difficult to find skill statistics***
***and***
***<u>Very</u> difficult to <u>compare</u> skill statistics.***

- Example #1 – one method:
  - Forecasts require data from single ground-based observatory, available 06:00 – 12:00 UT, when sunny, except Sundays.
  - Very high Skill reported!
    - Q: What happens Sunday night?
    - A: *Climatology*.

- Example #2 – comparing two methods:
  - Method #1 reports Heidke Skill Scores=0.50 for C1.0—C9.9 flares in 2003.
  - Method #2 reports Brier Skill Scores=0.36±0.03 for C1.0+ flares between 2001—2010.
    - Q: Which one's better?
    - A: *no way to tell.*

    - A: Direct, Coordinated Comparisons:
      *ask about our Flare Forecast Workshops; results coming soon....*

2) Standardized Data Sets:

- Removes bias if method performance is only reported for select data.
- If a method works well *only* on select, restricted data, *operational use will be limited.*

*Example*:
Method 3 only produces a forecast within 30° of solar disk center, and only for certain kinds of regions, and only for strong (M1.0+) flares.

For that subset of data:

| | |
|---|---|
| HK/P/T SS: | 0.21 |
| Brier SS: | 0.19 |

When “reference forecast” used to include all data in standard set:

| | |
|---|---|
| HK/P/T SS: | 0.07 |
| Brier SS: | 0.06 |